FINITE ELEMENT ANALYSIS OF STRENGTH CHARACTERISTICS OF LATERITE MASONRY AS A TWO-PHASE MATERIAL WITH CASE STUDY OF KUNNAMKULAM ANGADI PURA

A PROJECT REPORT

Submitted by

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TJE21CESE04

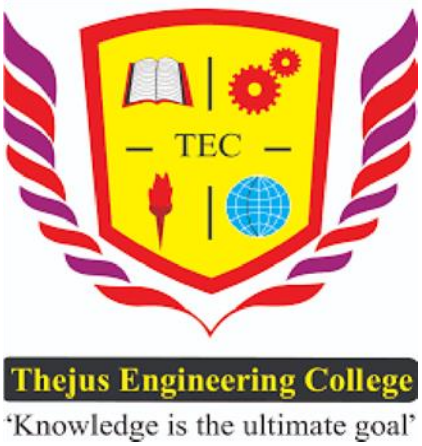
to

The APJ Abdul Kalam Technological University

In partial fulfillment of the requirements for the award of the Degree

of

Master of Technology
In
Structural Engineering



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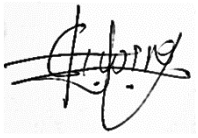
DECLARATION

I undersigned hereby declare that the project report "**FINITE ELEMENT ANALYSIS OF STRENGTH CHARACTERISTICS OF LATERITE MASONRY AS A TWO-PHASE MATERIAL WITH CASE STUDY OF KUNNAMKULAM ANGADI PURA**", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Dr.Vijayan P. This submission represents my ideas in my own words and where ideas or words of others have been included, I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.



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'Knowledge is the ultimate goal'

CERTIFICATE

This is to certify that the report entitled **"FINITE ELEMENT ANALYSIS OF STRENGTH CHARACTERISTICS OF LATERITE MASONRY AS A TWO-PHASE MATERIAL WITH CASE STUDY OF KUNNAMKULAM ANGADI PURA"** submitted by **BIMIN BIJU T (TJE21CESE04)** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Structural Engineering is a bonafide record of the project work carried out by him under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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I also convey my sincere thanks to all the faculty members of the Civil Engineering Department and my friends for their help and suggestions.

ABSTRACT

This project investigates the strength characteristics of laterite as a two-phase material composed of laterite blocks and mortar joints. The investigation is carried out through a series of analyses conducted on a masonry prism using ANSYS software. The construction industry often uses the “failure based on highly reduced design strength” thumb rule, which is considered at times to the extending even up to 1/10th of brick strength, to estimate the strength of masonry prisms at joint failure. However, this study challenges the validity and reliability of this thumb rule and aims to verify that it should not be adopted as a widely accepted practice. The study focuses on the strength and dimensions of the laterite blocks commonly used in Kunnamkulam Angadi, where structural issues are in the local housing known as “Angadi Puras.” The project emphasizes the importance of using standardized mortar in masonry construction and explores the structural deficiencies caused by weak mortar in Angadi Puras through ANSYS fem analyses. The software enables accurate and detailed structural assessments under various loading conditions the findings of this project provide valuable knowledge into the structural drawbacks of masonry structures with inadequate mortar strength and highlight the need to reassess and reject the “failure based on highly reduced design strength” thumb rule as a reliable standard. By exposing the limitations and deficiencies of this rule, results advocate for a more robust and accurate approach to evaluating masonry prism failure. The results from this study challenge the conventional wisdom and urge the construction industry to adopt improved and substantiated standards based on comprehensive analyses and empirical evidence.

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LIST OF ABBREVIATIONS AND NOTATIONS

FEA Finite Element Analysis

FRP Fiber-Reinforced Polymer

mm Millimetre

MPa Mega Pascal

kN Kilo Newton

CHAPTER 1

INTRODUCTION

1.1 GENERAL BACKGROUND

For ages, the Kerala region of India has been known for its unique and sustainable construction practices. One such traditional building material that has stood the test of time is the laterite block. Laterite, derived from the Latin word "later," meaning brick, is a naturally occurring material abundant in the region. The term laterite was first proposed by Buchanan in 1807. It has been extensively used as a masonry construction material in Kerala, imparting both strength and aesthetics to the structures. The origin of laterite block construction in Kerala can be traced back centuries, with numerous ancient temples, palaces, and dwellings standing as a testament to its durability. The use of laterite blocks gained prominence due to their availability, affordability, and remarkable thermal insulation properties, which help maintain a comfortable indoor environment in the region's tropical climate. The geological composition of laterite consists of clay, iron, aluminum, and other minerals, giving it a distinct reddish-brown color. The blocks are extracted from quarries and shaped into various sizes and dimensions to suit different construction requirements. One of the significant advantages of laterite blocks is their innate ability to withstand the region's heavy monsoon rains, humidity, and temperature variations without significant structural damage. Moreover, the use of laterite blocks aligns with sustainable construction practices, as it is an eco-friendly material that requires minimal energy consumption for its extraction and processing. This aspect makes laterite blocks an ideal choice for sustainable and environmentally conscious construction projects in Kerala.

In recent years, the traditional wisdom of using laterite blocks has gained renewed attention as architects and builders explore the revival of vernacular architecture. The aesthetic appeal and cultural significance of these blocks have led to their inclusion in contemporary designs, blending traditional craftsmanship with modern architectural principles. The Kerala region of India has a rich architectural heritage characterized by its distinctive use of laterite blocks as a primary construction material. These blocks, formed through a natural process of weathering, have been an integral part of the region's building practices for ages. Beyond their structural

properties, laterite blocks offer an inherent beauty that adds character to the buildings. The rich, earthy tones of the material complement the lush green surroundings of Kerala, creating a harmonious blend between the architecture and the natural landscape. The distribution of laterite in the west coast of India is shown in Figure 1.1.

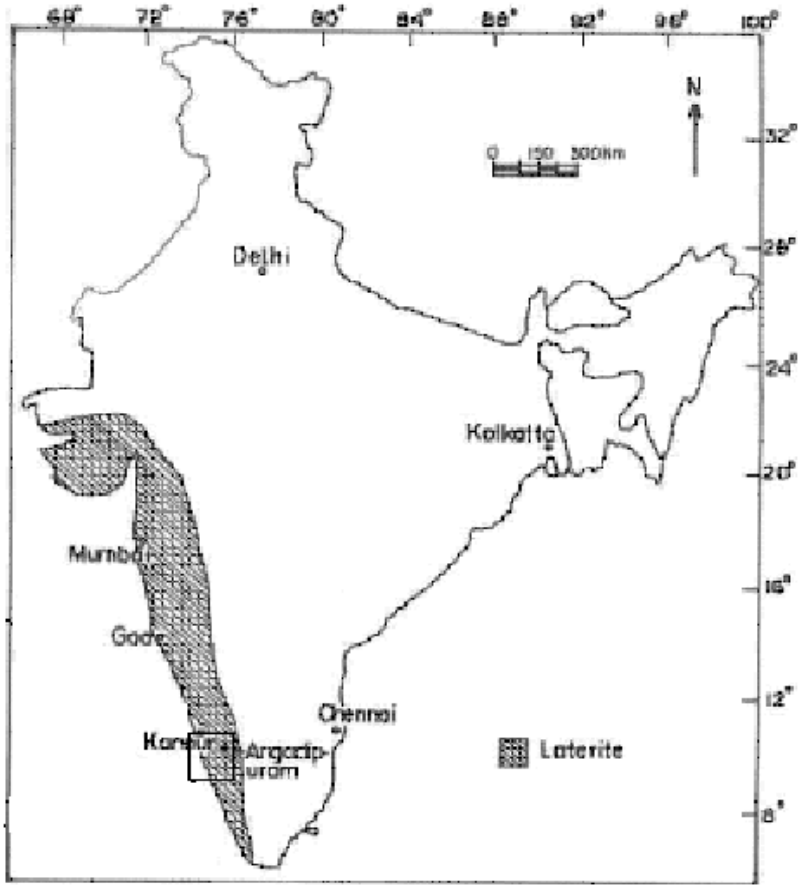


Fig1.1 Distribution of laterite in the west-coast of India

The Compressive strength can vary depending on the specific mix of minerals present in the laterite deposits and the compactness of the block. Durability is vital in a region like Kerala, which experiences high humidity and frequent rainfall. The blocks retain their strength and structural integrity over extended periods, requiring minimal maintenance. Kerala's tropical climate often brings scorching temperatures. However, laterite blocks exhibit exceptional thermal insulation properties, helping to keep the interiors of buildings cool. The high heat capacity and low thermal conductivity of laterite prevent excessive heat from entering the structure, creating a comfortable living environment. Laterite blocks have good

fire resistance properties, providing an added layer of safety to structures. They do not catch fire easily and can withstand high temperatures for an extended period without significant structural damage. This attribute enhances the overall safety of buildings constructed using laterite blocks. Due to their dense composition, laterite blocks offer effective sound insulation properties. They help reduce the transmission of noise from external sources, contributing to a quieter and more comfortable indoor environment.

In the realm of traditional construction practices in the Kerala region of India, mud mortar has stood as a time-honoured masonry construction material for centuries. Its prevalence and continued use can be attributed to its availability, affordability, and sustainable nature. Mud mortar, derived from locally sourced materials, has played a pivotal role in shaping the architectural heritage of Kerala, offering a blend of functionality, aesthetics, and environmental consciousness. Figure 1.2 illustrates the usage of mud mortar in masonry structures in Kunnamkulam Angadi.

Fig 1.2 The usage of mud mortar in masonry structures in Kunnamkulam Angadi.

Throughout the ages, the use of mud mortar has been deeply ingrained in the construction practices of Kerala. Its significance can be traced back to the region's rich cultural history, where traditional dwellings, temples, and palaces showcase the enduring qualities of this versatile material. Mud mortar has not only served as a bonding agent for constructing walls but also as a plastering material, lending a distinctive charm to the structures while ensuring structural stability. Mud mortar in Kerala is primarily composed of clay, silt, sand, and organic

materials such as straw or rice husk, which act as reinforcing agents. The mixture is carefully proportioned and prepared to achieve the desired consistency, workability, and strength. The use of organic additives enhances the plasticity of the mortar, making it easier to apply and shape during construction. One of the remarkable advantages of mud mortar lies in its sustainability. The materials used in its composition are locally available and renewable, reducing the environmental impact associated with long-distance transportation and manufacturing processes. Mud mortar also possesses excellent thermal insulation properties, helping to maintain comfortable indoor temperatures in the region's tropical climate. This natural insulation minimizes the need for artificial cooling and contributes to energy efficiency. Moreover, mud mortar exhibits a remarkable ability to absorb and release moisture, allowing for the regulation of humidity levels within buildings. This attribute is particularly valuable in a region like Kerala, which experiences high humidity and monsoon rains. The hygroscopic nature of mud mortar helps prevent moisture-related issues, such as mold growth and deterioration of building materials.

Despite its numerous advantages, the use of mud mortar in contemporary construction practices has faced challenges due to the emergence of modern building materials. However, there has been a growing interest in reviving and preserving traditional construction techniques in recent years. Architects, builders, and conservationists have recognized the intrinsic value of mud mortar in terms of cultural heritage, sustainability, and aesthetics. The significance of mortar joints in masonry structures extends beyond mere bonding; they are integral to the overall performance, stability, and durability of the construction. The Indian Standard Code of Practice for Plain and Reinforced Concrete (IS 4326:2013) and the Indian Standard Code of Practice for Masonry Structures (IS 1905:2017) serve as comprehensive references for masonry construction, encompassing critical aspects of mortar joint design, material selection, workmanship, and quality control.

The importance of mortar joints in masonry structures can be attributed to several key factors:

1. Structural Integrity: Mortar joints provide the necessary cohesion and load transfer between masonry units. The strength and proper design of mortar joints are essential for maintaining structural integrity and distributing loads effectively. Adhering to the

guidelines outlined in the Indian codes ensures the construction of robust and stable masonry structures capable of withstanding applied forces and external pressures.

2. Weather Resistance: Mortar joints act as a barrier against water penetration and environmental elements. By employing appropriate mortar composition, joint profiles, and construction techniques, masonry structures can effectively resist water ingress, reducing the risk of moisture-related issues such as dampness, efflorescence, and deterioration. Adhering to Indian standards ensures the selection of suitable mortar mixes and joint treatments that contribute to the long-term weather resistance of masonry.
3. Seismic Performance: Mortar joints play a crucial role in enhancing the seismic performance of masonry structures. Properly designed and constructed mortar joints facilitate the dissipation of seismic energy and improve the overall ductility and stiffness of the construction. Adhering to the seismic provisions outlined in the Indian codes ensures the adoption of adequate joint dimensions and reinforcement, contributing to structural resilience against seismic forces.
4. Workmanship and Quality Control: Mortar joints require skilled workmanship and adherence to strict quality control measures. The correct proportioning, mixing, and application of mortar are crucial for achieving the desired bond strength, joint thickness, and consistency. Following the guidelines stipulated in the Indian codes promotes quality control practices, such as mortar testing, curing methods, and inspection protocols, ensuring the integrity and performance of mortar joints in masonry structures.
5. Durability and Service Life: Mortar joints significantly influence the overall durability and service life of masonry structures. Properly designed and constructed mortar joints, in line with Indian standards, enhance the resistance to weathering, chemical attacks, and other forms of deterioration. Additionally, the appropriate selection of mortar types, such as lime-based or cement-based, considering the specific environmental conditions, helps prolong the service life of masonry structures.

This project has involves collecting real masonry structure samples to study mortar joints from Kunnamkulam Angadi. A particular residential replica "line houses" (angadi pura), is

seen in Kunnamkulam. The streets of these houses are exceedingly narrow. Figure 1.3 provides an aerial view of Kunnamkulam Angadi.

Fig1.3 Aerial view of Kunnamkulam Angadi.

The "Line Houses" are built on 3–5 cents of land on both sides of the street. The front room of the house functions as a shop while the rear room was used for residential purposes. There used to be rear yards for every so-called "Angadi pura" (townhouse) which was used for processing their agricultural products. The history of Kunnamkulam angadi dates back to 1789. During the invasion of Tippu Sultan in 1789, the Christians from Chattakulangara migrated to Kunnamkulam town after the invitation from Thalapilli Rajas. The Thalapilli Rajas provided residences and places of worship. In the past, the town was called Kunnankulangara and references can be seen in many British Archives about a neat and prosperous town which was predominantly Syrian Christians. With a rich heritage and cultural significance, Kunnamkulam Angadi has witnessed the passage of time and the evolution of its community. Have specifically designed the masonry blocks and joints to align with the

structural configuration observed in Angadi. The objective is to analyse the mortar joints in these samples and gain knowledge into their characteristics and performance. In the project, analysis was conducted to estimate the strength of masonry prisms at joint failure using the "highly reduced design strength" thumb rule. This thumb rule, which is sometimes extended up to 1/10th of the brick strength, is commonly used to estimate the failure strength of masonry prisms. Figure 1.4 provides the necessary information, Table 8 (Basic Compressive Stresses for Masonry after 28 days) on page 16 of IS 1905(1987), the Indian Standard code of practice for masonry construction, was referred to. This table provides valuable data regarding the basic compressive stresses that masonry can withstand after 28 days of curing.

IS : 1905 - 1987

TABLE 8 BASIC COMPRESSIVE STRESSES FOR MASONRY (AFTER 28 DAYS)

(*Clause* 5.4.1)

Sl No.	Mortar Type (Ref Table 1)	Basic Compressive Stresses in N/mm² Corresponding to Masonry Units of Which Height to Width Ratio does not Exceed 0·75 and Crushing Strength in N/mm² is not less than											
		3·5	5·0	7·5	10	12·5	15	17·5	20	25	30	35	40
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	H1	8·35	0·50	0·75	1·00	1·16	1·31	1·45	1·59	1·91	2·21	2·5	3·05
2	H2	8·35	0·50	0·74	0·96	1·09	1·19	1·30	1·41	1·62	1·85	2·1	2·5
3	M1	8·35	0·50	0·74	0·96	1·06	1·13	1·20	1·27	1·47	1·69	1·9	2·2
4	M2	0·35	0·44	0·59	0·81	0·94	1·03	1·10	1·17	1·34	1·51	1·65	1·9
5	M3	0·25	0.41	0·56	0·75	0·87	0·95	1·02	1·10	1·25	1·41	1·55	1.78
6	L1	0·25	0·36	0·53	0·67	0·76	0·83	0·90	0·97	1·11	1·26	1·4	1·06
7	L2	0·25	0·31	0·42	0·53	0·58	0·61	0·65	0·69	0·73	0·78	0·85	0·95

Note 1 — The table is valid for slenderness ratio up to 6 and loading with zero eccentricity.

Note 2 — The values given for basic compressive stress are applicable only when the masonry is properly cured.

Note 3 — Linear interpolation is permissible for units having crushing strengths between those given in the table.

Note 4 — The permissible stress for random rubble masonry may be taken as 75 percent of the corresponding stress for coarsed walling of similar materials.

Note 5 — The strength of ashlar masonry (natural stone masonry of massive type with thin joints) is closely related to intrinsic strength of the stone and allowable working stress in excess of those given in the table may be allowed for such masonry at the discretion of the designer.

Fig 1.4 Table 8 of IS 1905(1987)

This information would provide a clear explanation of the methodology used to estimate the strength of masonry prisms at joint failure and highlight the reliance on the "highly reduced design strength" thumb rule and the specific reference to Table 8 in IS 1905(1987). By studying the mortar joints in masonry structures, concerning Indian codes and standards, this project aims to provide valuable results into optimizing the design, construction, and performance of mortar joints. By adhering to the guidelines outlined in the codes, masonry professionals can ensure the safety, durability, and functionality of masonry structures in India, further advancing the state of masonry construction practices in the country.

1.2 OBJECTIVES

1. Re-evaluating the Validity of the “failure based on highly reduced design strength” thumb rule, which is considered at times to the extending even up to 1/10th of brick strength, challenging its adoption as a construction industry standard by through comprehensive analysis like;

i. Vertical loading on masonry prism
ii. Out-of-plane horizontal loading on masonry prism
iii. In-plane horizontal loading on masonry prism

2. Investigating the role of cement mortar instead of mud mortar in laterite prism through comprehensive analysis like;

i. Vertical loading on masonry prism
ii. Out-of-plane horizontal loading on masonry prism
iii. In-plane horizontal loading on masonry prism

3. To determine the compressive strength of laterite stones collected from Kunnamkulam angadi and evaluate the thickness of the mortar bond through an outdoors-based study.

4. Structural defects in angadi puras are field investigated and structural retrofitting methods are recommend.

CHAPTER 2
LITERATURE REVIEW

2.1 GENERAL

Studies on laterite as a construction material are rare. However, there is literature on laterite soil and geological research on laterite. A few studies on laterite are presented to help in understanding the qualities of the mineral. Papers on block/brick masonry are included to learn more about prism studies or the reaction of masonry structures to lateral loads.

2.2 REVIEW OF PAPERS

Andreaus U (1996) analysed failure criteria of masonry panels under In-plane loading have been investigated, focusing on three primary modes of failure: slipping of mortar joints, cracking of clay bricks, and splitting of mortar joints, as well as middle plane spalling. This study connects appropriate strength criteria to each collapse mode. Slip-induced failure is modeled using a frictional law that incorporates nonlinear shear strength dependence on normal stress. Splitting is explained by the maximum tensile strain criterion, assuming orthotropic non-symmetric elasticity of the material. Spalling occurs when the maximum compressive stress (Navier criterion) is reached under biaxial loading. Strength parameters were determined based on experimental results and compared with established criteria from existing literature. The proposed failure criteria demonstrated good agreement with experimental findings, within the limitations of small-size panels, single wythes, solid units, regular mortar joints, and in-plane loads. The potential application of these criteria to real-world cases is also demonstrated, including a specific example illustrating how to predict the failure load and mode of a particular masonry panel. It should be noted that this discussion focuses solely on the in-plane behaviour of solid-brick, single-wythe masonry and does not consider the effects of Out-of-plane bending caused by eccentrically applied loads or lateral instability.

Das S (2008) has conducted field and laboratory studies on recently quarried stones as well as deterioration diagnostics of Goan laterite monuments using the Basilica of Bon Jesus, India, as a case study. Water intrusion has been discovered to be the primary source of the majority of the monument's flaws. Even when compared to regular brick, Goan laterite was shown to be poor in compression and flexure. Therefore, rather than strength, water tightness

was credited with masonry's durability.

Gumaste (2007) examined the Andaman and Nicobar Islands (India) structures' performance in December 2004 using wire-cut and table-molded Indian bricks along with various mortar types to study the characteristics of brick masonry. For stiff-brick/soft-mortar and soft-brick/stiff-mortar combinations, the strength and elastic modulus of brick masonry were assessed under compression. Prisms and wallets were both investigated. In Western nations, brick masonry typically uses bricks that are robust and stiff in comparison to the mortar used. These bricks are discovered to have elastic moduli ranging from 3500 to 34000 MPa and compressive strengths between 15 and 150 MPa. India's bricks, on the other hand, have substantially lower elastic moduli (300-15000 MPa) and strengths (3-20 MPa). The stress-related state manifested in the pressure range of 3500 to 34000 MPa. India's bricks, on the other hand, exhibit comparatively lower strengths (3–20). The degree of stress that develops in the masonry's brick-and-mortar components relies on how elastic those components are in comparison. Bricks will be under triaxial compression and mortar will be under uniaxial compression and bilateral tension when bricks are significantly softer than mortar and the brick-mortar interface bond is maintained until masonry failure. In this case, the tension cracking of the mortar in the joint is what causes the masonry to fail.

Karantoni F.V. and Fardis M.N. (1992) have studied the behaviour of and damage inflicted on stone-masonry buildings. The results from a finite element analysis show that Out-of-plane bending and the transfer of Out-of-plane lateral loads to the transverse walls cause most of the damage. They have concluded that finite element analysis can be used to improve our understanding of the seismic behaviour of masonry buildings and to develop and assess techniques of seismic strengthening.

Kasthurba A.K. and Santhanam M. (2005) carried out a detailed study of laterite building stones from four major quarries in widely scattered locations of the Malabar region, Kerala. The compressive strength of laterite blocks was evaluated according to Indian standard specifications. According to this study, the strength values of laterites depend on the specimen size and its geometry. In the reported results, the compressive strength of most of the specimens tested was below 3.5 MPa, which is the prescribed minimum for use in laterite stone masonry, as per IS 3620-1979.

Kasthurba A.K. Santhanam M. and Mathews M.S. (2006) studied the weathering forms

and properties of laterite building stones used in historic monuments of Western India. This study found that the deterioration of laterite masonry may be caused due to a variety of causes. They have identified dampness as a major factor that induces deterioration and hence protection from dampness would prolong the life of laterite monuments.

Kasthurba A.K., Santhanam M., and Mathews M.S.(2007) tested laterites from numerous quarries in Kerala's Malabar region to investigate laterite stones used for construction. The experimental results of the compressive strength of machine-cut laterites from the Malabar region, which are widely available commercially, range from 1.3 MPa to 4.3 MPa. Their research indicates that laterite stones exhibit a wide range of engineering features depending on the location of the quarry and the depth within a quarry. It was observed that while water absorption increases with depth, specific gravity and compressive strength decrease, which causes the quality of laterite blocks in the deeper strata to deteriorate. Once more, it can be seen from a comparison of wet and dry strengths that saturation causes a large loss in strength (47–75%). Hence, it is advised that laterite masonry be shielded from moisture. Additionally, it was found that laterite stones with a dark reddish brown to red hue, obtained from the top of the profile, typically had stronger strength, a higher specific gravity, and less water absorption, making them suitable for use in construction.

Kaushik H.B., Rai D.C., and Jain S.K.'s (2007) experimental findings showed that the brick masonry's modulus of elasticity fluctuated between 250 and 1100 times its prism strength.Masonry prism compressive strengths predicted by the proposed finite element model are about 19% less than the experimental values.

McNary S.W. and Abrams D.P (1985) investigated the strength and deformation of clay-unit masonry were investigated under uniaxial concentric compressive force, along with biaxial tension-compression tests of bricks and triaxial compression tests of mortar. The study focused on examining the behaviour of soft cement-lime mortar and stiff fired-clay bricks. The internal stress state resulting from shear stresses at the brick mortar interface consisted of triaxial compression in the mortar and bilateral tension coupled with axial compression in the brick. This stress state led to the initiation of vertical splitting cracks and eventual failure. Experimental properties of the brick and mortar were used as inputs for a numerical model, and the calculated prism strengths and deformations were compared with experimental results to validate the theory. The failure of the prism primarily occurred due

to lateral tensile splitting of the masonry unit, with the mortar inducing the tensile stresses. These stresses exhibited disproportionate increases with compressive forces, owing to the nonlinear deformational properties of the mortar. The strength of the prism also depended on the strength of the masonry units, which experienced bi-axial tensile and uniaxial compressive stresses, as well as applied loads or lateral instability.

Murty C.V.R., Rai D.C., Jain S.K., Kaushik H.B., Mondal G., and Dash S.R. (2006) have investigated how the Andaman and Nicobar Islands in India fared during the Great Sumatra Earthquake and Indian Ocean Tsunami of December 2004. While many relatively recently built masonry buildings have collapsed due to Out-of-plane instability of the slender walls and poor connection or no connection to the surrounding structural elements, several old masonry structures on the islands performed well during the earthquakes, revealing the high quality of masonry construction practice prevalent in India up until the first half of the twentieth century.

Rai D.C. and Goel S.C. (1996) studied the seismic strengthening of unreinforced masonry piers with steel elements. They considered the in-plane behaviour of masonry piers. The strengthening system showed significant improvement in stiffness and ductility.

Rao S.S., Reddy V.B.V., and Jagadish K.S. Studied strength characteristics of soil-cement block masonry. They have concluded that bed joint thickness has a significant influence on masonry strength and its effect will depend on the ratio of mortar strength to block strength. Based on experimental results they have recommended 10 to 12mm thickness of bed joints for soil-cement block masonry.

Reddy V.B.V., Lal R., and Rao N.K.S (1995) investigated how soil-cement block masonry prism strength and deformation behaviour are affected by bed-joint thickness, elastic characteristics of the soil-cement blocks, and mortar. It was discovered that the relationship between the block's modulus and the mortar's modulus affects the compressive strength of masonry. When the ratio of block to mortar modulus is greater than 1, the compressive strength of masonry falls as the thickness of the mortar joint increases. The ratio and Poisson's ratios of the mortar and the masonry units have an impact on the lateral tensile stresses that arise in the structure.

Şahin(2010) has developed a simple assistant program named ANSeismic, for implementing earthquake analyses of structures with ANSYS and SAP2000, finite element codes. The

structural models constructed in ANSYS may be analysed by just loading the analysis file developed with ANSeismic. ANSeismic program is free software and can be used as a tool in the time history analysis of structures by researchers. It can be downloaded from MATLAB Central.

Sarangapani G., Reddy V.B.V., and Jagadish K.S (2005) have investigated the influence of bond strength on the compressive strength of masonry was examined through an experimental program utilizing local bricks and mortars. The elastic modulus of the bricks used was significantly lower (15 times less) than that of the mortar. The experimental results indicated that an increase in bond strength led to a corresponding increase in the compressive strength of the masonry. This suggests that the compressive strength of the masonry prism is more responsive to variations in the bond strength between bricks and mortar compared to the compressive strength of the mortar itself.

Vyas Ch.U.V. And Reddy V.B.V. (2010) have developed A three-dimensional non-linear finite element model has been created using a micro-modeling approach to accurately estimate the compressive strength and crack pattern of solid block masonry. The finite element model incorporates multi-linear stress-strain relationships to simulate the non-linear behaviour of both the solid masonry unit and the mortar. The predicted compressive strengths of the masonry prisms obtained from the developed finite element model are approximately 19% lower compared to the experimental values. These findings provide valuable informations into the applied loads and potential lateral instability of the masonry structures.

2.3 RESEARCH GAP

1. Validity of the Thumb Rule: There is a lack of relevant research on the validity of the existing thumb rule that states the strength of a masonry prism is considered as 1/10th of the brick strength at joint failure. The limited literature available does not provide sufficient evidence to support or challenge this rule. Therefore, further investigation is needed to determine the accuracy and reliability of this thumb rule in predicting the strength of masonry prisms.
2. Study on Laterite as a Construction Material: There is a scarcity of research on the use of laterite as a construction material. Laterite, commonly found in tropical regions, has been historically used for construction purposes due to its availability and cost-

effectiveness. However, there is a lack of comprehensive studies investigating its mechanical properties, durability, and suitability for different structural applications. Further research is required to explore the potential of laterite as a construction material and establish appropriate design guidelines and construction practices for its usage.

2.4 METHODOLOGY

The methodology for the study is outlined as follows:

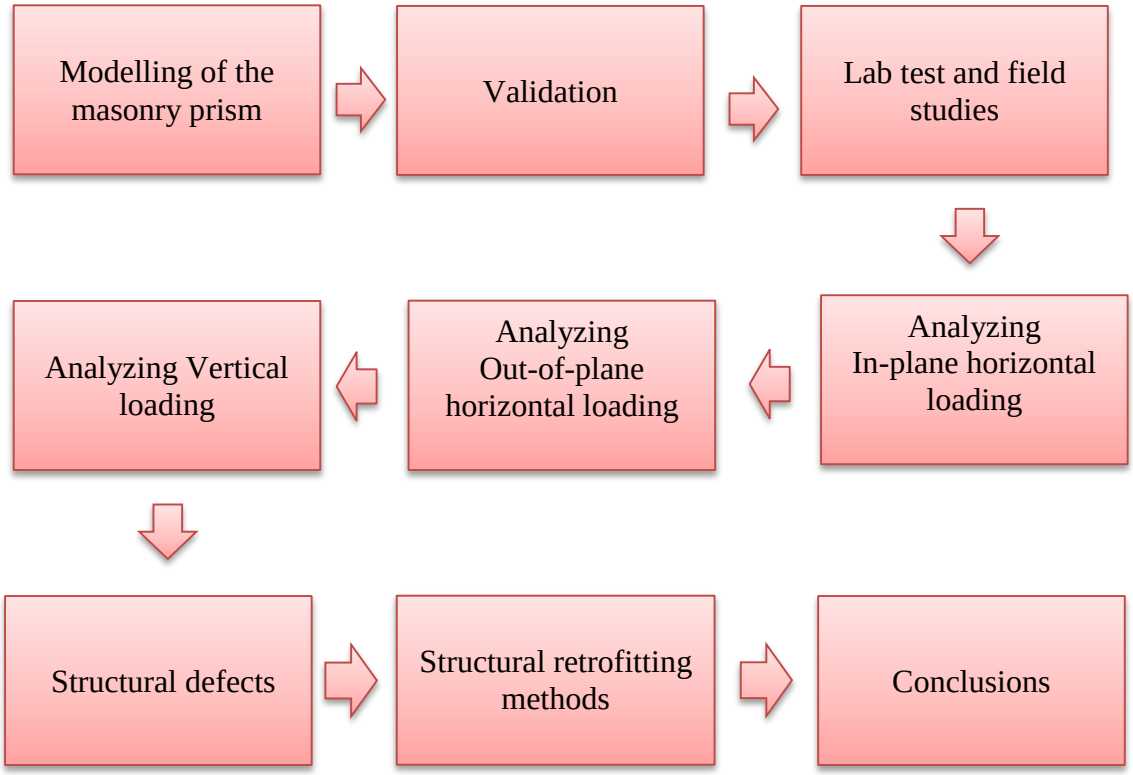


Fig 2.1 Flow chart of methodology

1. Modelling of the masonry prism was performed using ANSYS Workbench 2022. This software was chosen for its advanced capabilities in simulating structural behaviour.
2. The validation of the model was conducted to ensure its accuracy and reliability in predicting the performance of the masonry prism. Various experimental data and real-world observations were compared with the simulation results.
3. A field study was conducted to determine the compressive strength of laterite stones

collected from Kunnamkulam Angadi. Additionally, the thickness of the mortar bond was assessed through outdoor-based investigations.

4. The investigation focused on analysing the effects of laterite block and mortar on the pressure loading within the laterite masonry prism.
5. Out-of-plane horizontal loading behaviour of laterite block and mortar was analysed to assess their response under external forces applied perpendicular to the plane of the masonry prism.
6. In-plane horizontal loading behaviour of laterite block and mortar was analysed to examine their response to forces applied within the plane of the masonry prism.
7. Structural defects present in Angadi Puras (local masonry structures) were investigated to identify any existing issues or weaknesses in their construction.
8. Various structural retrofitting methods were investigated to explore potential solutions for improving the stability and performance of the Angadi Puras.
9. The study concludes by summarizing the findings, discussing their implications, and providing recommendations for further research.

CHAPTER 3
FINITE ELEMENT ANALYSIS

3.1 GENERAL

Finite Element Method (FEM) analysis is a powerful numerical technique used in engineering and applied sciences to solve complex problems involving structural analysis, heat transfer, fluid dynamics, and electromagnetics. FEM analysis divides the domain of a problem into smaller, finite-sized elements, allowing for the approximation of the behaviour of the system under study. It is widely employed in various industries, including aerospace, automotive, civil engineering, and manufacturing, to predict the performance and behaviour of structures and systems. The fundamental concept behind FEM analysis is to discretize a continuous problem into a finite number of elements, each representing a small portion of the entire domain. These elements are interconnected at specific points known as nodes, forming a mesh that approximates the geometry of the system. By applying governing equations and boundary conditions to these elements, FEM analysis enables the calculation of the system's response to applied loads, thermal effects, or other physical phenomena. The advantages of using FEM analysis are numerous. Firstly, it provides a flexible approach to handle complex geometries and boundary conditions. By breaking down the problem into smaller elements, FEM analysis allows for the representation of irregular shapes and varying material properties, making it applicable to a wide range of engineering scenarios. FEM analysis offers a comprehensive understanding of structural performance. It allows engineers to assess stress distribution, deformation, and failure modes in a structure, aiding in design optimization and structural integrity assessment. The technique also facilitates the evaluation of different design alternatives, enabling engineers to make informed decisions and achieve optimal designs that meet performance, safety, and efficiency requirements. Moreover, FEM analysis plays a vital role in the virtual prototyping and simulation of engineering systems. By simulating the behaviour of a structure under various operating conditions, FEM analysis reduces the need for costly physical prototypes and extensive testing. This not only saves time and resources but also enables engineers to explore a broader range of design possibilities and make design improvements before physical realization.

3.2 ANSYS

ANSYS is a powerful engineering simulation software widely used in the field of masonry analysis. With its robust capabilities and comprehensive suite of tools, ANSYS enables engineers and researchers to analyse and evaluate the behaviour of masonry structures under various loading conditions. By utilizing ANSYS, professionals can gain valuable understanding into the structural performance, strength, and stability of masonry constructions, ultimately aiding in the design, optimization, and assessment of such structures. ANSYS provides a wide range of features and functionalities that make it well-suited for masonry analysis. It employs advanced numerical methods and finite element analysis (FEA) techniques to simulate and predict the response of masonry elements and assemblies. This allows for a detailed examination of complex behaviours, including material nonlinearity, cracking, deformations, and failure mechanisms, which are critical considerations in masonry engineering. One of the key uses of ANSYS in masonry analysis is the determination of the structural capacity and safety of masonry structures. By modelling the individual masonry units, mortar joints, and their interactions, ANSYS can assess the load-carrying capacity of different components and identify potential failure modes. This information is crucial in designing structures that can withstand applied loads, such as gravity loads, wind, seismic forces, or thermal effects. Furthermore, ANSYS aids in evaluating the behaviour of masonry structures under different environmental conditions. By considering factors like temperature changes, moisture effects, and long-term creep, ANSYS enables the analysis of the durability and performance of masonry elements over time. This information helps engineers make informed decisions regarding material selection, construction techniques, and maintenance practices. ANSYS also facilitates the exploration of design alternatives and optimization of masonry structures. By iteratively modifying parameters such as geometry, material properties, and reinforcement configurations, engineers can assess the impact of these changes on structural performance. ANSYS provides valuable i understanding into structural behaviour, allowing for the development of optimized designs that meet specific performance criteria and regulatory requirements. ANSYS plays a vital role in masonry analysis by providing a comprehensive set of tools and capabilities for simulating and evaluating the behaviour of masonry structures. Its ability to model complex behaviours, assess structural capacity, analyse durability, and optimize designs makes it an

indispensable tool for engineers and researchers working in the field of masonry engineering. By harnessing the power of ANSYS, professionals can enhance the safety, reliability, and efficiency of masonry structures in various applications, ranging from historical preservation to modern construction projects. ANSYS 22 was used to analyse the Masonry prism in this project.

3.3 MODELLING USING ANSYS

A masonry prism constructed using the stack-bonded technique and composed of laterite blocks was modeled for analysis. The dimensions of the prism are 360 mm x 220 mm x 890 mm for validation and 1060mm x 220 mm x 620mm mm for analysis. The prism consists of five laterite blocks, each measuring 360 mm x 220 mm x 170 mm, and is separated by four mortar joints, each measuring 360 mm x 220 mm x 10 mm for validation and 340 mm x 220 mm x 100 mm with mortar joints of 20 mm thick at the head joint and 30 mm thick at the bed joint for analysis. This stack-bonded masonry configuration is a common construction method where the blocks are stacked vertically with each block directly on top of the other, ensuring vertical alignment. The laterite blocks, known for their durability and weather resistance, are popularly used in the region due to their availability and suitability for the local climate conditions. The dimensions provided represent the overall size of the masonry prism, including both the blocks and mortar joints. The laterite blocks are tightly fitted together in a horizontal and vertical arrangement, creating a solid masonry assembly. The mortar joints, which act as the bonding material between the blocks, provide cohesion and structural integrity to the prism. By modeling this stack-bonded laterite masonry prism, engineers and researchers can analyse its structural behaviour under various loading conditions. This analysis helps to assess the overall strength, stability, and deformation characteristics of the masonry assembly. Understanding the performance of such masonry configurations is crucial for ensuring the structural safety and durability of buildings constructed using laterite blocks in the region.

3.3.1 SOLID 185

SOLID185 is an element type available in ANSYS, specifically designed for three-dimensional solid modelling and analysis. It is a 20-node solid element capable of accurately capturing complex geometries and modelling various material behaviours. The SOLID185 element offers several key features that make it suitable for a wide range of structural analysis

applications. These include:

1. Geometric Flexibility: SOLID185 can handle complex geometries and irregular shapes, allowing for an accurate representation of real-world structures. It supports both linear and quadratic shape functions, providing flexibility in meshing and capturing geometric details.
2. Material Modelling: This element supports isotropic, orthotropic, and anisotropic material properties. It can simulate linear elasticity, nonlinear material behaviour (such as plasticity, creep, and hyper elasticity), and thermal effects. This allows engineers to accurately represent a wide range of materials and their response under different loading and environmental conditions.
3. Accurate Stress Analysis: SOLID185 provides accurate stress predictions, particularly in regions with stress concentrations or complex loadings. Compatibility with Other Elements: SOLID185 can be seamlessly combined with other element types within ANSYS, such as beam, shell, or contact elements, to create multi-physics models or analyse complex structures that involve different types of elements.
4. Mesh Refinement: SOLID185 allows for mesh refinement in critical regions where higher accuracy is required. By locally refining the mesh, engineers can capture localized stress concentrations and accurately predict the behaviour of the structure.
5. Nonlinear Analysis: SOLID185 is suitable for both linear and nonlinear analysis. It can handle large deformations, material nonlinearities, and contact interactions, enabling the simulation of complex structural behaviour under extreme loading conditions. Figure 3.1 illustrates SOLID185.

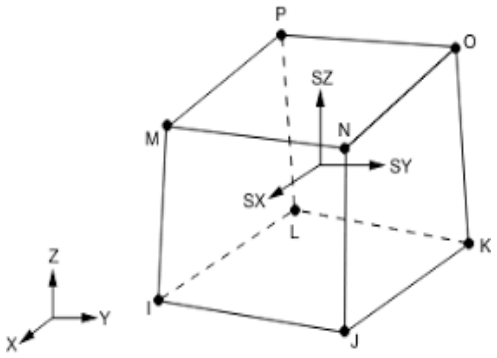


Fig 3.1 SOLID185

3.3.2 CONTA174

CONTA174 is used to represent contact and sliding between 3-D target surfaces and a deformable surface defined by this element. The element applies to 3-D structural and coupled-field contact analyses. It can be used for both pair-based contact and general contact. The element is defined by eight nodes (the underlying solid or shell element has mid-side nodes). It can degenerate to a six-node element depending on the shape of the underlying solid or shell elements. CONTA174 supports isotropic and orthotropic coulomb friction.

3.3.2 TARGE170

TARGE170 is used to represent various 3-D "target" surfaces for the associated contact elements. The contact elements themselves overlay the solid, shell, or line elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170. For rigid target surfaces, these elements can easily model complex target shapes. For flexible targets, these elements will overlay the solid, shell, or line elements describing the boundary of the deformable target body. Figure 3.2 illustrates CONTA174 and TARGE170.

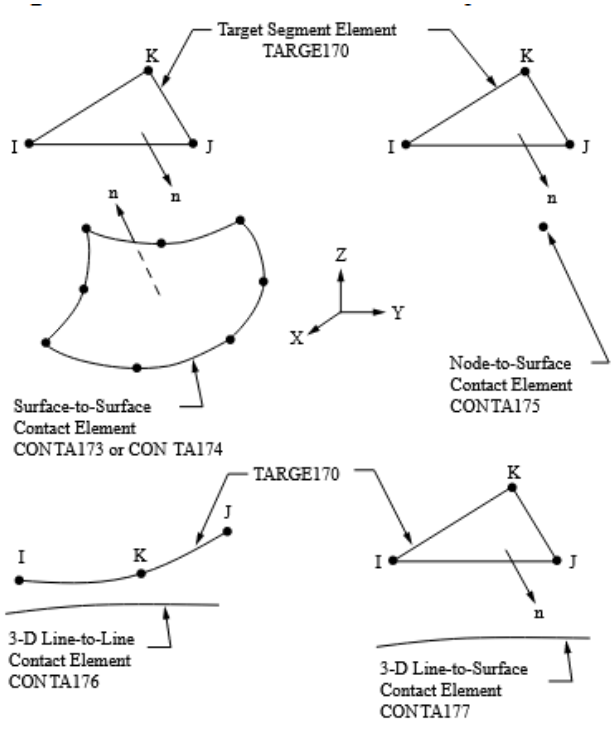


Fig 3.2 CONTA174 and TARGE170

CHAPTER 4

METHODOLOGY AND VALIDATION

4.1 GENERAL

In this study, the analysis of the masonry prism was conducted using the finite element method (FEM), with the utilization of ANSYS Workbench 2022 version. The aim was to achieve accurate results by considering the material properties of laterite, mud mortar, and cement mortar. This comprehensive approach not only enables a more precise analysis but also enhances the understanding of the structural response and performance of the masonry prism under different loading conditions.

4.2 VALIDATION

The validation process involves a comparative analysis between the results obtained from ANSYS simulations and the findings presented in the journal article titled "Seismic Response of Laterite Masonry Structures" by Sujatha Unnikrishnan.

4.2.1 GEOMETRY AND MATERIAL PROPERTIES

The ANSYS Workbench 2022 software was used to carry out the finite element modelling. A five blocks-high stack-bonded laterite masonry prism was modelled using ANSYS software.

Table 4.1 gives the reference values and range of values of material properties considered.

Table 4.1 Material properties of masonry prism

Sl.no	Material properties	Reference Value	Range
1	Poisson's ratio of laterite	0.15	0.15,0.20
2	Poisson's ratio of cement mortar	0.15	0.15,0.20
3	Modulus of elasticity of laterite(MPa)	1300	750,1300
4	Modulus of elasticity of cement mortar(MPa)	3000	3000
5	Thickness of mortar(mm)	10	20

The prism size of 360 mm x 220 mm x 890mm, made up of 5 laterite blocks of size 360 mm x 220 mm x 170 mm and 4 mortar joints of 360 mm x 220 mm x 10 mm, was considered. The modulus of elasticity of laterite and mortar determined experimentally were given as input in the analysis. Poisson ratios of laterite and mortar were taken from previous studies. The blocks and the joints were modelled, assuming a perfect bond between them.

4.3 RESULTS OF VALIDATION

The results obtained from the ANSYS are compared with the ANSYS analysis of Sujatha Unnikrishnan. The figure 4.1 below depicts the prism modelled in ANSYS for validation.

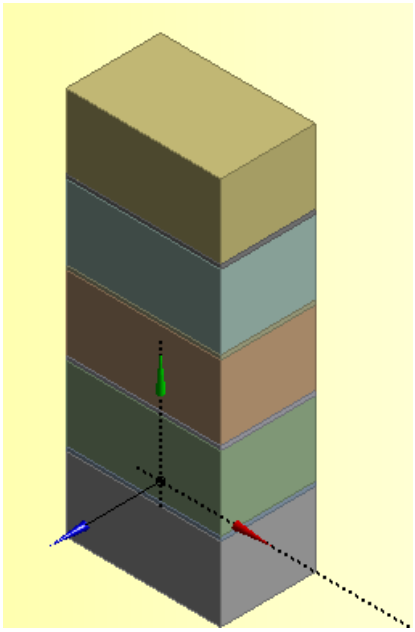


Fig 4.1 Prism modelled in ANSYS for validation

To understand the influence of different factors on the laterite masonry prism strength, it was analysed by varying parameters. For all the analyses, a representative pressure of 2 MPa was applied on the top surface of the laterite masonry prism. The varying parameters used in this parametric study were Poisson's ratios of laterite and mortar, the modulus of elasticity of laterite and mortar, and the thickness of the mortar joint.

4.3.1 Poisson's Ratios of Laterite and Mortar

In the first analysis, the following material properties and dimensions were used:

- Poisson's ratio of laterite: 0.15
- Poisson's ratio of mortar: 0.15
- Modulus of elasticity of laterite: 1300 MPa
- Modulus of elasticity of mortar: 3000 MPa
- The thickness of mortar: 10 mm

These parameters were considered to simulate the behaviour of the laterite and mortar materials within the model. The maximum principal stress (lateral tensile) in the mortar joint, for a vertically applied pressure of 2 MPa on the laterite masonry prism, was obtained as 0.382 Mpa in the journal. In the present analysis, the maximum principal stress (lateral tensile) in the mortar joint was found to be 0.408 MPa, which represents a 6% increase compared to the journal value. The Figure 4.2 illustrates the comparison between the analysis figures presented in the journal article and the corresponding analysis results obtained in present ANSYS analysis.

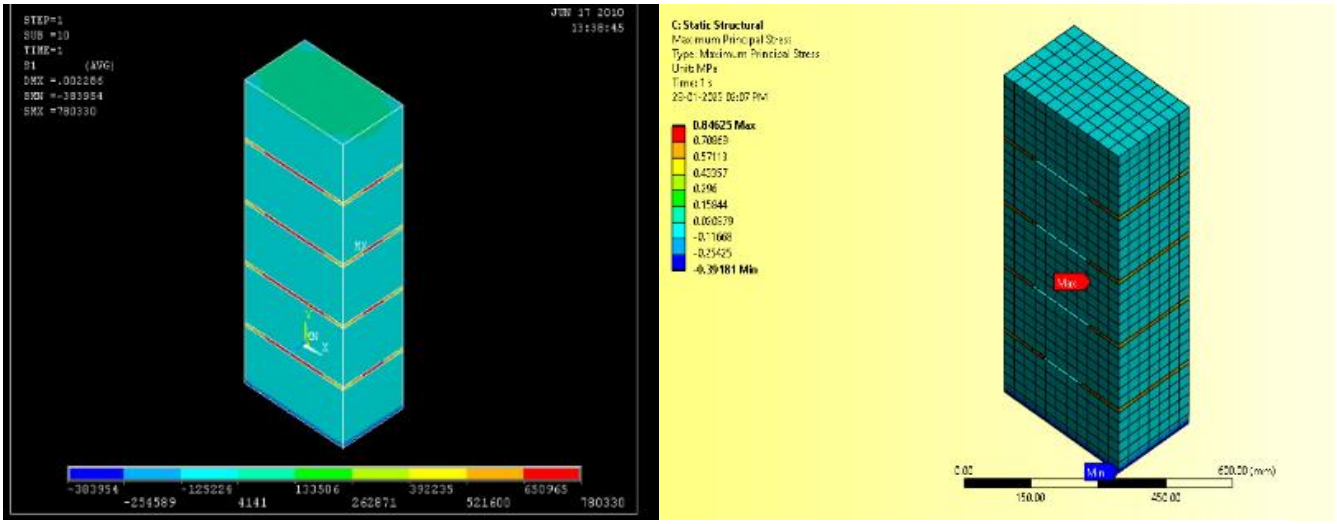


Fig 4.2 Analysis figure presented in the journal article and the corresponding analysis results obtained in present ANSYS analysis

4.3.2 Modulus of Elasticity of Laterite and Mortar

In the second analysis, the following material properties and dimensions were used:

- Poisson's ratio of laterite: 0.15

- Poisson's ratio of mortar: 0.15
- Modulus of elasticity of laterite: 750 MPa
- Modulus of elasticity of mortar: 3000 MPa
- The thickness of mortar: 10 mm

Reduction in the modulus of elasticity of laterite blocks or an increase in the modulus of elasticity of mortar, results in increase in the lateral tensile stresses in mortar joint, in the laterite masonry prism, at a given vertical pressure. As the ratio of modulus of elasticity of laterite block to modulus of elasticity of mortar is reduced, there is an increase in the lateral tensile stresses in the mortar. These parameters were considered to simulate the behaviour of the laterite and mortar materials within the model. The Figure 4.3 illustrates the comparison between the analysis figures presented in the journal article and the corresponding analysis results obtained in present ANSYS analysis.

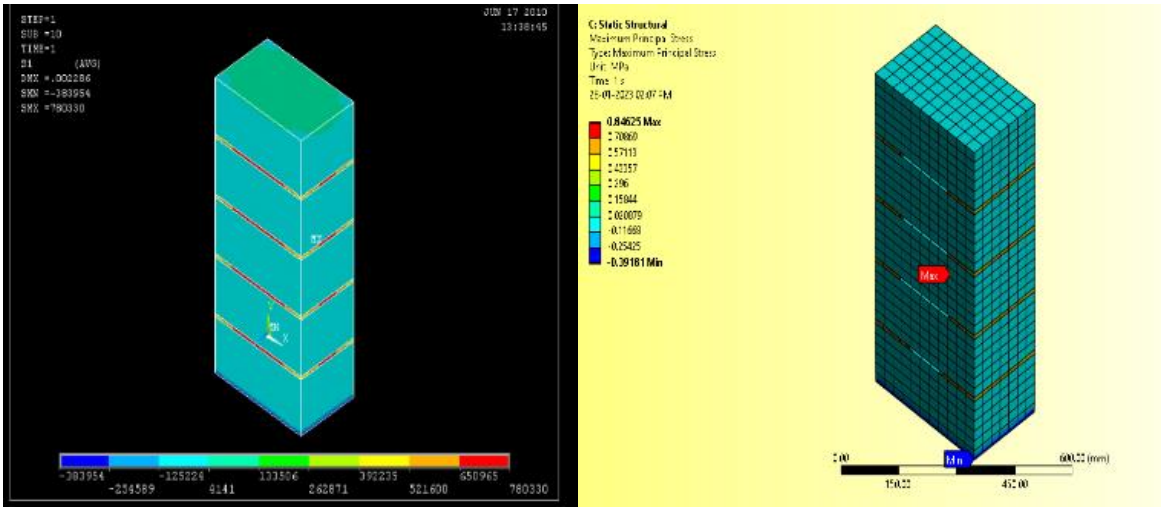


Fig 4.3 Analysis figures presented in the journal article and the corresponding analysis results obtained in present ANSYS analysis

When the modulus of elasticity of laterite was reduced from 1300 MPa to 750 MPa, maximum principal stress in mortar was observed to have increased from 0.382 MPa to 0.78 MPa The increase was more than 100 percent as per the journal. In the analysis, the maximum principal stress (lateral tensile) in the mortar joint was found to be .846 MPa, which represents the same 100% increase compared to the journal value.

4.3.3 Mortar Joint Thickness

In the third analysis, the following material properties and dimensions were used:

- Poisson's ratio of laterite: 0.15
- Poisson's ratio of mortar: 0.15
- Modulus of elasticity of laterite: 1300 MPa
- Modulus of elasticity of mortar: 3000 MPa
- The thickness of mortar: 20 mm

In the first case the maximum principal stress in the mortar was observed as 0.382 MPa and in the second case 0.324 MPa Thickness of the mortar joint was increased from 10 mm to 20 mm the lateral tensile (principal stress) stresses in the mortar has reduced by 15% as per journal. In the analysis, the Maximum principal stress (lateral tensile) in the mortar joint for 20mm was obtained as 0.357 MPa. The lateral tensile stresses in mortar have reduced by 14% which is 1%decrease from journal value. .The Figure 4.4 illustrates the comparison between the analysis figures presented in the journal article and the corresponding analysis results obtained in present ANSYS analysis.

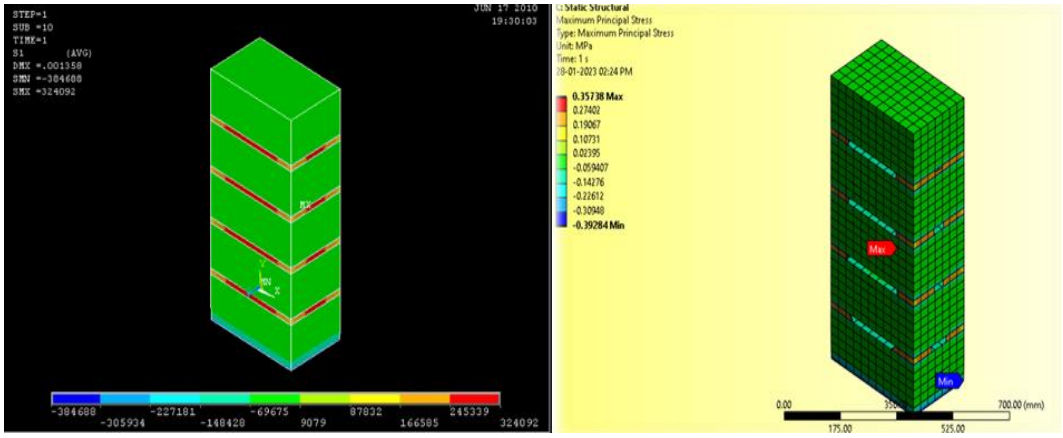


Fig 4.4 Analysis figures presented in the journal article and the corresponding analysis results obtained in present ANSYS analysis.

4.4 SUMMARY

The current study conducted a finite element analysis to validate the results obtained in a reference paper regarding the behaviour of masonry structures using laterite as a construction

material. The analysis revealed that the results were generally consistent, but with some slight variations. In the current study, the maximum principal stress (lateral tensile) in the mortar joint was found to be 0.408 MPa, a 6% increase compared to the value reported in the reference paper. Additionally, when the thickness of the mortar joint was increased from 10 mm to 20 mm, the reference paper reported a 15% reduction in lateral tensile stresses in the mortar. In the current analysis, the maximum principal stress in the mortar joint for the 20 mm thickness was obtained as 0.357 MPa, which corresponds to a 14% reduction compared to the reference value. While this deviation indicates a slight discrepancy, the general trend of reduced stress with increased mortar thickness was consistent. Overall, the finite element analysis in the current study validated the findings of the reference paper with slight variations in stress magnitudes. Therefore, the model is validated.

CHAPTER 5
EXPERIMENT AND FIELD STUDY ON LATERITE MASONRY STRUCTURES FROM ANGADI

5.1 GENERAL

A laboratory test was conducted on the laterite samples collected from one of the oldest pura in Kunnamkulam Angadi to determine their compressive strength. The aim was to understand the material properties of the laterite and assess its suitability for construction purposes. Additionally, a comprehensive field study was conducted in Angadi to determine the optimal sizes of mortar joints for both bed joints and head joints in the masonry construction. The study involved visiting 15 different "puras" within Angadi to gather data on the existing mortar joint sizes used in the region. By averaging the values obtained from the field study, an average mortar joint size was determined for use in the analysis and future construction projects. This approach ensured that the chosen mortar joint sizes aligned with the traditional construction practices observed in Angadi, while also accounting for the variations found within different areas of the township. The combination of the laboratory test results and the field study provided valuable understanding into the compressive strength of laterite. Overall, the data gathered from the laboratory test and field study was used for the subsequent analysis. Figure 5.1 below depicts typical laterite mortar structures observed in Kunnamkulam Angadi.

Fig 5.1 Typical laterite mortar structures observed in Kunnamkulam Angadi

5.1.1 LATERITE COMPRESSIVE STRENGTH

As the initial step of the project, compression test was conducted on laterite samples collected from Kunnamkulam Angadi. Three laterite specimens, labeled A, B, and C, were tested in a compression testing machine. Figure 5.2 below illustrates the three laterite samples that were tested.

Fig 5.2 The three laterite samples that were tested.

The size of each specimen was 340×220×100 mm. During the testing process, the compressive stress values observed for the laterite specimens were recorded. Specimen A had a compressive stress value of 3.168 MPa, specimen B had a value of 2.673 MPa, and specimen C had a value of 2.888 MPa. Figure 5.3 illustrates the failure patterns of a tested specimen.

Fig 5.3 Illustrates the failure patterns of a tested specimen.

To determine the average compressive strength of the laterite, the values obtained from the

three specimens were averaged. The resulting average compressive strength was calculated as 3 MPa. Specimen. The resulting average compressive strength was calculated as 3 MPa. Table 5.1 shows calculation of compressive test on Laterite

Table 5.1: Calculation of compressive test on laterite

SAMPLE	SIZE mm	AREA mm^2 A	WEIGHT Kg	FAILURE LOAD kN W	COMPRESSIVE STRESS N/mm^2 W / A
A	340×220×100	74800	16.75	237	3.168
B	340×220×100	74800	11.95	200	2.673
C	340×220×100	74800	14.59	216	2.888
AVERAGE COMPRESSIVE STRESS					3 N/mm^2

According to the indian standards of Laterite Stone Block for Masonry IS 3620:1989, the minimum compressive strength requirement for laterite blocks is specified as 2.5 MPa. In the testing conducted on my laterite samples, the average compressive strength was determined to be 3 MPa.Comparing the obtained compressive strength of 3 MPa to the codal minimum value of 2.5 MPa, it can be concluded that the laterite blocks tested exceed the minimum requirement specified by the Indian Standards.

According to masonry unit strength method in national building code of India (NBC) the compressive strength of a masonry unit can be estimated by multiplying the compressive strength of the individual materials by certain factors, known as adjustment factors. This method is based on the assumption that the compressive strength of a masonry unit is primarily controlled by the strength of the individual materials that make up the unit, such as the brick or block and mortar.

According to this method, the compressive yield strength and tensile ultimate strength can be estimated as follows:

i. Compressive yield strength = 0.45 times the compressive strength
ii. Tensile ultimate strength = 10% of the compressive strength

Using these relationships, if the maximum compressive strength of the laterite block is 3 MPa, then:

i. Compressive yield strength = 0.45 x 3 MPa = 1.35 MPa
ii. Tensile ultimate strength = 10% x 3 MPa = 0.3 MPa

The values mentioned were taken for analysis purposes in future steps of the project.

5.1.2 INVESTIGATION ON LATERITE MORTAR ARRANGEMENT

After conducting extensive fieldwork in Kunnamkulam Angadi, it was discovered that there is a significant variation in the size of laterite blocks used in the construction of puras. This indicates that there is no standardized block size in the region, and each house may have its unique block dimensions based on historical and local construction practices. Furthermore, during the fieldwork, it was observed that there was a considerable variation in the thickness of mortar joints between different houses. This inconsistency suggests that there is no uniformity in the application of mortar joints during the construction process. Figure 5.4 depicts the arrangement of mortar joints in the masonry structures observed in Kunnamkulam Angadi. The figure illustrates the specific pattern or arrangement of mortar joints between the individual bricks or blocks used in the construction.

Fig 5.4 Arrangement of mortar joints

To ensure accurate modeling and analysis in ANSYS, it was necessary to determine the average thickness of the mud mortar joints based on the site visits to 15 Angadi puras in Kunnamkulam Angadi. Figure 5.5 shows the field investigation conducted in Kunnamkulam Angadi.

Fig 5.5 Field investigation conducted in Kunnamkulam Angadi.

This data served as a representative sample of the prevailing mortar joint sizes in the region. Table 5.2 below depicts data collected by field investigation

Table 5.2: Data collected by field investigation

SL NO	LOCATION	BED JOINT THICKNESS mm	HEAD JOINT THICKNESS mm
1	EAST BAZAAR	30	10
2	EAST BAZAAR	40	30
3	EAST BAZAAR	50	20
4	EAST BAZAAR	20	10
5	EAST BAZAAR	10	10
6	SOUTH BAZAAR	20	20
7	SOUTH BAZAAR	20	20
8	SOUTH BAZAAR	30	20
9	SOUTH BAZAAR	15	10

10	SOUTH BAZAAR	20	10
11	WEST BAZAAR	20	20
12	WEST BAZAAR	50	30
13	WEST BAZAAR	30	30
14	WEST BAZAAR	50	30
15	WEST BAZAAR	40	30
AVERAGED (mm)		30	20

Based on the collected data, it was determined that the average thickness of the head joint, which connects the vertical surfaces of the laterite blocks, is 20mm. On the other hand, the average thickness of the bed joint, which connects the horizontal surfaces of the blocks, is 30mm. Figure 5.6 illustrates the mortar joints with 20mm head joint and 30mm bed joint.

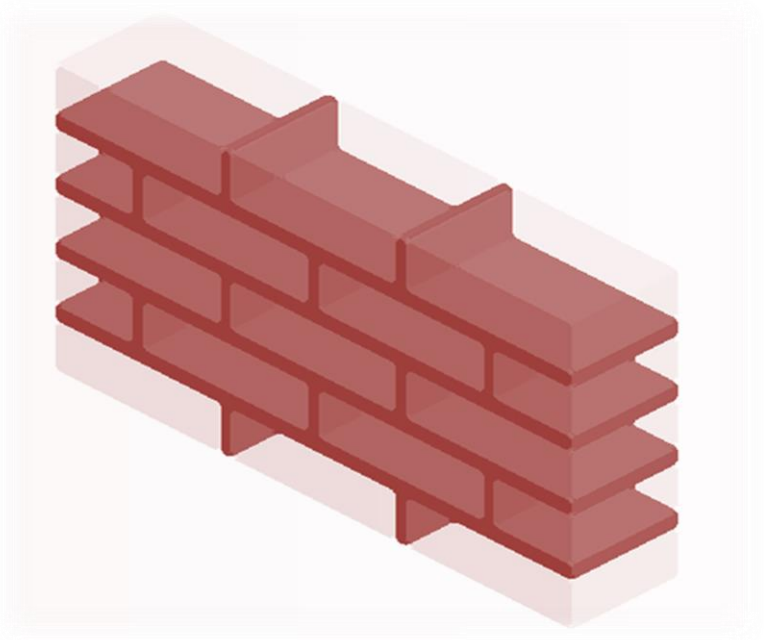


Fig 5.6 Mortar joints with 20mm head joint and 30mm bed joint.

5.1.3 ANSYS MODEL

For the masonry analysis, a prism model was created with dimensions of 340 mm x 220 mm x 100 mm. The model incorporated mortar joints with specific thicknesses, where the head joint had a thickness of 20 mm and the bed joint had a thickness of 30 mm. Figure 5.7 illustrates the masonry prism designed according to the provided data.

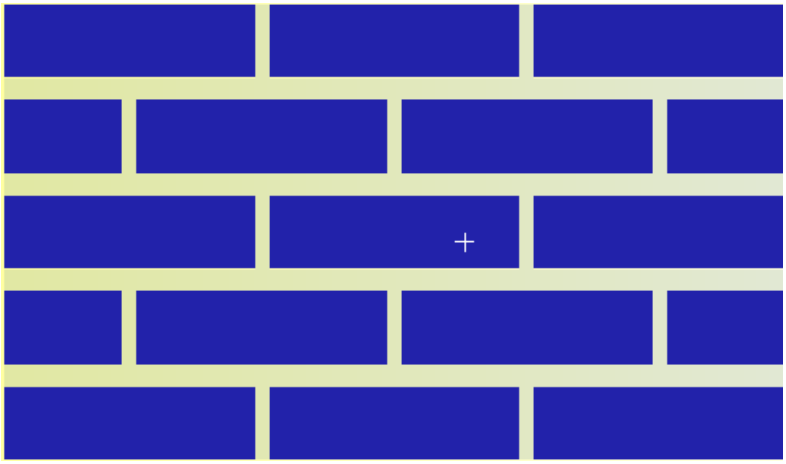


Fig 5.7 Masonry prism designed according to the provided data.

By considering the actual dimensions and mortar joint thicknesses observed during the fieldwork, the model aimed to accurately represent the structural configuration of the masonry construction in the region. The prism model served as a representative sample for further analysis to evaluate the structural behaviour and performance of the masonry construction.

5.2 SUMMARY

i. The compressive strength of the laterite collected from Kunnamkulam Angadi was determined to be 3 MPa.

ii. Based on the obtained average compressive strength value, the laterite samples do not meet the minimum strength criteria for masonry construction as per the specified standard.

iii. Based on the collected data, it was determined that the average thickness of the head joint and bed joint had a thickness of 20mm and 30 mm respectively.

CHAPTER 6
LATERITE MASONRY PRISM ANALYSIS

6.1 GENERAL

To gain a comprehensive understanding of the importance of mortar joints in masonry structures, this project conducted analyses on the previously mentioned masonry prism model. The model incorporated both mud mortar and cement mortar to assess their respective effects on the structural behaviour. Various loading conditions were applied to the masonry prism to simulate different real-world scenarios. Figure 6.1 illustrates the different types of loading conditions that were analysed in the study. The figure showcases the various scenarios or situations in which the masonry structures were subjected to different types of loads. This may include vertical loads, horizontal loads, or a combination of both. The purpose of analyzing different loading conditions is to understand the behaviour and response of the masonry structures under various realistic and potentially challenging scenarios.

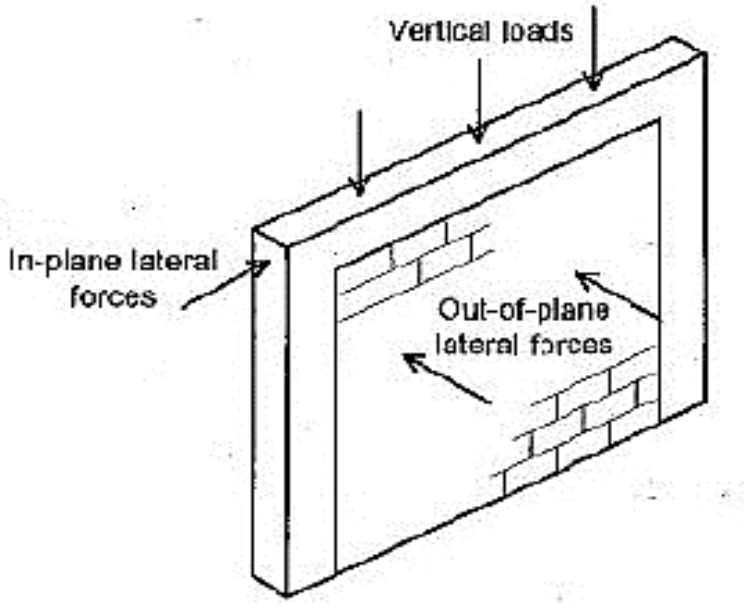


Fig 6.1 Different types of loading conditions

Vertical loading simulated the effect of gravity and applied downward forces to the masonry prism. This loading condition helped assess the load-carrying capacity, stress distribution, and overall stability of the structure under vertical loads. Out-of-plane horizontal loading involved applying forces perpendicular to the plane of the masonry prism. This loading

condition replicated situations such as wind pressure or lateral forces acting on the structure. By analyzing the response to Out-of-plane horizontal loading, researchers could gain into the structure's resistance to external forces and potential weaknesses in its stability. In-plane horizontal loading referred to applying forces parallel to the plane of the masonry prism. This loading condition evaluated the behaviour of the structure when subjected to horizontal forces, such as seismic activity or lateral loads. Analyzing the response to In-plane horizontal loading helped identify the masonry's resistance to shear forces and its ability to withstand horizontal stresses. By analyzing the masonry prism under different loading conditions using both mud mortar and cement mortar, this project aimed to compare and understand the performance differences. The results of these analyses would provide valuable into the role of mortar joints in distributing forces, enhancing structural integrity, and mitigating potential failures in masonry structures. The findings from these analyses would contribute to the broader understanding of the significance of mortar joints in masonry construction. The knowledge gained could inform construction practices, retrofitting strategies, and design improvements, ultimately enhancing the safety and durability of masonry structures in various real-world scenarios.

6.2 MATERIAL PROPERTY

The following material properties values were taken from previous studies conducted on this materials. Material properties were assigned for the analysis of the laterite, mud mortar, and cement mortar:

1. Laterite:

i. Compressive ultimate strength: 3 MPa.
ii. Compressive yield strength -1.35 MPa
iii. Tension ultimate strength -0.3 MPa
iv. Poisson's Ratio: 0.15.
v. Modulus of Elasticity: 1200 MPa
vi. Bulk modulus: 572 MPa
vii. Shear modulus: 522 MPa

2. Mud Mortar:

i. Compressive ultimate strength-1 MPa
ii. Compressive yield strength -0.5 MPa
iii. Tension ultimate strength -0.1 MPa
iv. Poisson's Ratio: 0.147
v. Modulus of Elasticity: 1170 MPa
vi. Bulk modulus: 552.41 MPa
vii. Shear modulus: 510.03 MPa

3. Cement Mortar:

i. Compressive yield strength - 4 MPa
ii. Tension ultimate strength -0.5 MPa
iii. Poisson's Ratio: 0.15.
iv. Modulus of Elasticity: 1200 MPa
v. Bulk modulus: 571 MPa
vi. Shear modulus: 521.74 MPa

These material properties were utilized in the analysis to simulate the behaviour of the laterite blocks, mud mortar, and cement mortar under different loading conditions. By accurately representing the properties of these materials, the analysis aimed to provide into the structural performance and behaviour of the mortar in a prism.

6.3 VERTICAL LOADING

Pressure loading on masonry structures from the top is a critical aspect that influences the structural behaviour and stability of the construction. When a masonry structure is subjected to pressure loading from the top, it experiences vertical forces that can significantly impact its overall performance and integrity. Understanding the effects of such loading conditions is essential for ensuring the safety and longevity of masonry structures. Pressure loading can arise from various sources, including dead loads, live loads, and environmental factors such

as wind or seismic forces. These loads exert pressure on the top surface of the masonry, causing compression and transferring forces vertically throughout the structure. The distribution of pressure across the masonry elements is influenced by factors such as the magnitude and distribution of the load, the size and arrangement of the masonry units, and the properties of the mortar joints. Properly designed and constructed mortar joints play a vital role in transmitting and distributing the applied loads, enhancing the structural capacity of the masonry. Additionally, the behaviour of mortar joints, including their shear strength and ability to withstand compression, becomes crucial in managing the pressure-induced forces. Understanding the effects of pressure loading on masonry structures is of utmost importance for engineers, architects, and construction professionals involved in the design, analysis, and retrofitting of such structures. It enables them to ensure structural adequacy, identify potential vulnerabilities, and implement appropriate measures to enhance the performance and resilience of masonry constructions.

6.3.1 VERTICAL LOAD ANALYSIS OF MASONRY WITH MUD MORTAR

In the first analysis, the structure consisting of laterite blocks with mud mortar was subjected to varying pressures ranging from 0.1 MPa to 1.2 MPa. Figure 6.2 illustrates the application of pressure from the top

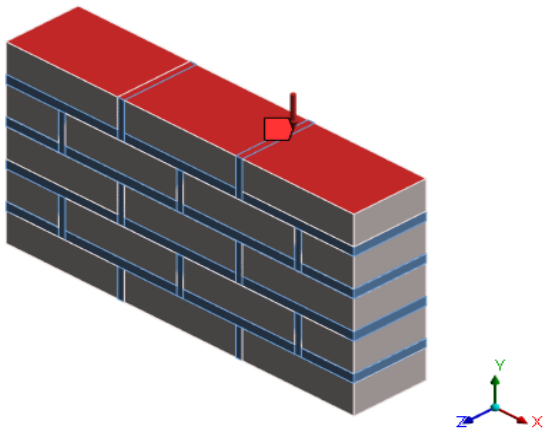


Fig 6.2 Application of pressure from the top

The purpose of this analysis was to determine at what point the structure would cross its yield point and potentially experience failure. By applying increasing pressures, the analysis aimed to evaluate the response of the structure and identify the critical pressure threshold at which

the materials surpassed their yield points. The yield point refers to the stress level at which a material undergoes significant plastic deformation or permanent deformation. The analysis would have involved monitoring the stress distribution within the structure, particularly in the laterite blocks and the mud mortar joints. It would have focused on identifying regions or elements where the stress exceeded the yield strength of the materials, indicating a potential failure. The normal stress values were recorded for each direction to understand the load-bearing capacity and potential failure modes of the structure. These values provide crucial into the performance and structural integrity of the laterite masonry prism under loading conditions. The figure 6.3 and figure 6.4 highlights the regions within the laterite block and mud mortar where the stress values reached their peak. These areas indicate potential points of vulnerability and indicate the need for further investigation to understand the load transfer mechanisms and stress redistribution within the masonry prism.

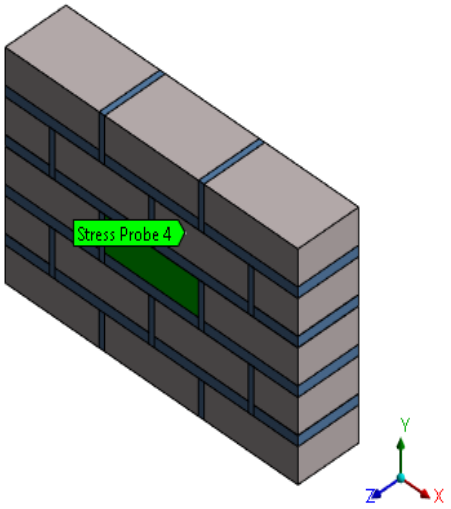


Fig 6.3 Laterite block with peak stress values

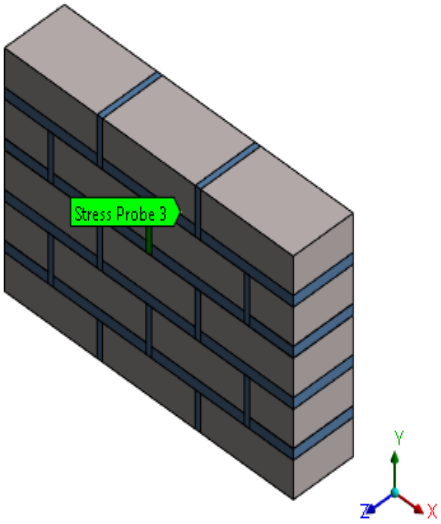


Fig 6.4 Mud mortar with peak stress values

The table provides a clear overview of the normal stress values in the x, y, and z directions at each loading step.

Table 6.1 Normal stress values in the x, y, and z directions in Laterite

Load MPa	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
0.1	0.002	-0.09	0
0.3	0.001	-0.299	0
0.5	0.002	-0.49	0
0.7	0.014	-0.698	0
1.2	0.025	-1.1	0.001

Table 6.2 Normal stress values in the x, y, and z directions in Mud mortar

Load MPa	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
0.1	0	-0.09	0
0.3	0	-0.299	0
0.5	0	-0.49	0
0.7	0	-0.686	0.001
1.2	0.003	-1	0.002

During the analysis, it was observed that the highest peak stress occurred in the head joint of the mud mortar. This finding suggests that the head joint is the most critical area in terms of stress concentration within the prism. Additionally, the failure of the prism was first observed in the mud mortar, indicating that it is the weakest component in the assembly. Notably, the failure in the mud mortar predominantly occurred under compression. This implies that the mud mortar reached its compressive stress limit when subjected to vertical stress loading or

pressure from the top at the maximum applied value of 1.2 MPa. The compressive stress reached its yield point in the mud mortar, highlighting the critical stress level at which the material exhibited deformation .Furthermore, the normal stresses in the y-axis direction were found to reach the yield stress level during the analysis.

6.3.2 VERTICAL LOAD ANALYSIS OF MASONRY WITH CEMENT MORTAR

In this case analysis, the prism consisting of laterite blocks with cement mortar was subjected to varying pressures ranging from 1 MPa to 3MPa. Figure 6.5 illustrates the imposition of pressure from the top.

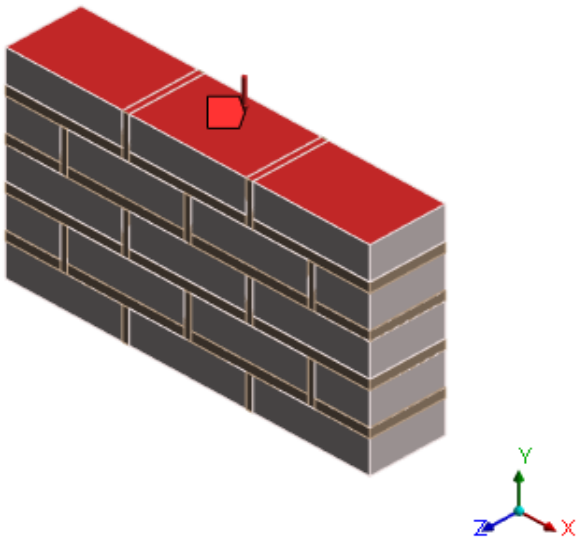
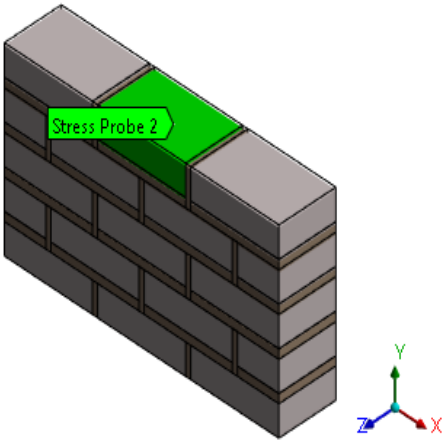


Fig 6.5 Imposition of pressure from the top.

The purpose of this analysis was to determine at what point the structure would cross its yield point and potentially experience failure. By applying increasing pressures, the analysis aimed to evaluate the response of the structure and identify the critical pressure threshold at which the materials surpassed their yield points. The analysis involved monitoring the stress distribution within the structure, particularly in the laterite blocks and the cement mortar joints. It focused on identifying regions or elements where the stress exceeded the yield strength of the materials, indicating a potential failure. By employing the normal stress as criteria, on the distribution of stresses within the prism was carefully evaluated. The normal stress values were recorded for each direction to understand the load-bearing capacity and

potential failure modes of the structure. These values provide crucial into the performance and structural integrity of the laterite masonry prism under Out-of-plane horizontal loading conditions.

The figure 6.6 and figure 6.7 highlights the regions within the laterite block and cement mortar where the stress values reached their peak. These areas indicate potential points of vulnerability and indicate the need for further investigation to understand the load transfer mechanisms and stress redistribution within the masonry prism.



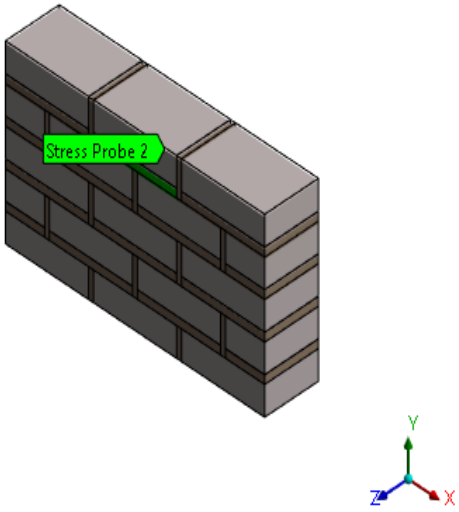


Fig 6.6 Laterite block with peak stress values Fig 6.7 Cement mortar with peak stress values

The obtained data for laterite and cement mortar, are presented in Table 6.3 and Table 6.4, respectively, is summarized in the table below. The table provides a clear overview of the normal stress values in the x, y, and z directions at each loading step.

Table 6.3 Normal stress values in the x, y, and z directions in Laterite

Load MPa	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
1	0.002	-0.998	0
1.5	-0.036	-1.48	0.002

3	0.06	-3	0.001

Table 6.4 Normal stress values in the x, y, and z directions in Cement mortar

Load MPa	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
1	-0.003	-0.978	0.002
1.5	-0.004	-1.467	0.003
3	-0.008	-3	0.007

Through this investigation, it was observed that the highest peak stress occurred in the laterite blocks themselves, rather than in the mortar joints. The failure of the structure was primarily observed in the laterite blocks, and this failure occurred in compression. Specifically, as the vertical stress loading or pressure from the top increased to 3 MPa, the laterite blocks experienced a critical point where the yield stress level was reached. This point, where the material begins to deform permanently, was attained in compression. This finding highlights the significance of mortar in the overall behaviour and performance of masonry structures, particularly in distributing and transferring loads. In masonry construction, mortar serves as a binding material that holds the individual masonry units together, forming a cohesive system. One of the key functions of mortar is to evenly distribute loads across the masonry assembly. As external loads, such as vertical or lateral forces, act on the structure, the mortar effectively transfers these loads from one masonry unit to another. By providing a strong and continuous bond between the units, the mortar ensures that the load is shared and dispersed throughout the structure, rather than being concentrated in localized areas. Moreover, the properties of the mortar, such as its compressive strength and adhesion, significantly influence the load distribution within the masonry system. A well-designed and properly proportioned mortar mix ensures optimal load-bearing capacity and structural integrity. If the mortar is weak or improperly mixed, it may result in stress concentrations, leading to potential failure points or reduced overall strength of the masonry structure. Additionally, the stiffness and flexibility of

the mortar play a crucial role in accommodating differential movement and thermal expansion/contraction between the masonry units. By allowing slight movement and providing a degree of flexibility, the mortar helps mitigate the effects of potential stress-induced cracking or structural instability.

6.4 SUMMARY

The study focused on the behaviour of masonry structures constructed using laterite and different types of mortar, specifically mud mortar and cement mortar. The findings of the study are as follows:

1. Laterite and Mud Mortar:

   i. Failure occurred in the mud mortar under a vertical stress of 0.5 MPa.
   ii. The failure in the mud mortar was first observed in compression.
   iii. The compressive stress level in the mud mortar was significantly lower than the compressive stress level in the laterite when failure occurred.
   iv. Failure of the mud mortar was observed when the laterite reached approximately 2.09% of its compressive stress level.

2. Laterite and Cement Mortar:

   i. Failure occurred in the laterite and cement mortar under a lateral load of 3 MPa.
   ii. The failure in the laterite was first observed in compression.
   iii. The compressive stress level in the laterite was significantly lower than the compressive stress level in the cement mortar when failure occurred.
   iv. Failure of the laterite was observed when the cement mortar reached approximately 0.26% of its compressive stress level.

6.5 OUT-OF-PLANE HORIZONTAL LOAD

In the field of structural engineering, the analysis and understanding of different loading conditions on masonry structures are of paramount importance. One such critical loading scenario is Out-of-plane horizontal loading, which occurs when external forces are applied perpendicular to the plane of the masonry wall or structure. This loading condition can have

significant implications for the stability and structural integrity of masonry constructions. Out-of-plane horizontal loading is encountered in various real-life situations, such as wind loads, seismic events, and accidental impacts. Understanding the behaviour of masonry structures under such loading conditions is essential for ensuring their safety and resilience. When subjected to Out-of-plane horizontal loading from the top, the masonry structure experiences bending and shearing forces. The response of masonry structures to Out-of-plane horizontal loading depends on several factors, including the mechanical properties of the masonry materials, the geometry of the structure, the presence of reinforcement, and the quality of construction. The mortar joints, which connect the individual masonry units, play a crucial role in distributing the applied loads and transferring them between the units. Figure 6.8 illustrates the application of Out-of-plane horizontal loading.

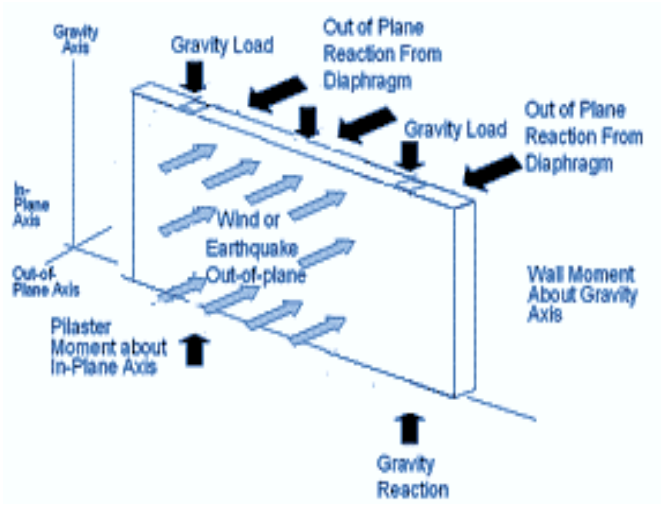


Fig 6.8 Out-of-plane horizontal loading.

Understanding the effects of Out-of-plane horizontal loading on masonry structures aids in designing robust and resilient buildings. It helps engineers in making informed decisions regarding appropriate reinforcement strategies, retrofitting techniques, and the selection of suitable materials to enhance the structural integrity and resistance to Out-of-plane horizontal loading.

6.5.1 OUT-OF-PLANE ANALYSIS OF MASONRY WITH MUD MORTAR

In the case analysis, a laterite prism with mud mortar was utilized to investigate the response of the masonry structure under out of plane loading conditions. Figure 6.9 illustrates the

imposition of Out-of-plane horizontal loading on prism with mud mortar.

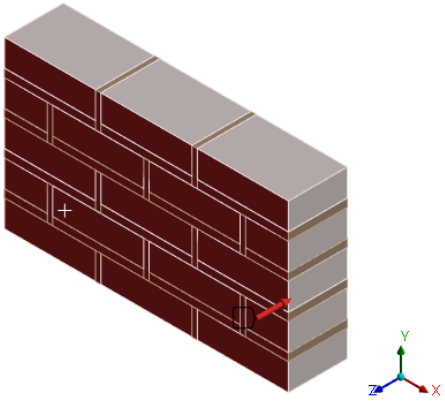


Fig 6.9 Imposition of Out-of-plane horizontal loading on prism with mud mortar.

To explore the behaviour of the prism across a range of stress levels, the load was systematically varied as a percentage of the maximum load. For the analysis of Out-of-plane horizontal loading on a laterite masonry prism with mud mortar, the following loading conditions were applied starting from 1950N, 4875N, 9750N, 14625N and 19500N. The purpose of these loading intervals is to simulate progressive loading on the masonry prism and observe its response to increasing external forces. By employing the normal stress as criteria, the distribution of stresses within the prism was carefully evaluated. The normal stress values were recorded for each directions to understand the load-bearing capacity and potential failure modes of the structure. Figure 6.10 and 6.12 represent the tension face of the laterite block and mud mortar, showcasing areas where tensile stresses were prominent.

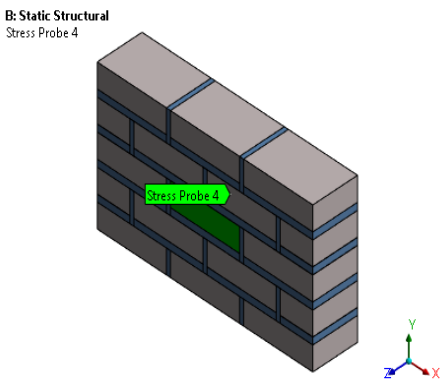


Fig 6.10 Tension face of laterite block

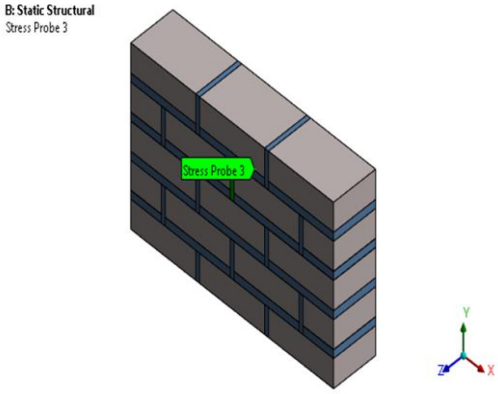


Fig 6.12 Tension face of mud mortar

Figure 6.11and 6.12 depicts the compression face of the laterite block and mud mortar, illustrating regions where compressive stress are present.

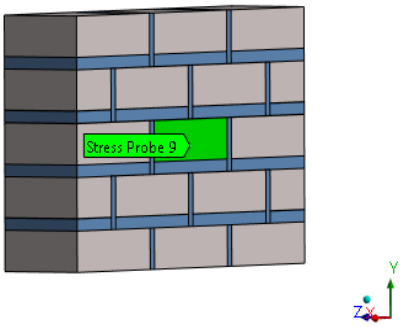


Fig 6.11 Compression face of laterite block

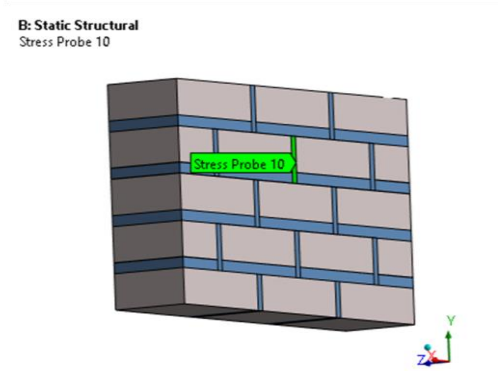


Fig 6.13 Compression face of mud mortar

By analyzing and visualizing the areas of highest stress concentration within the laterite blocks and mud mortar joints, it becomes possible to identify critical zones that require attention during the design and construction process. The Table 6.5 and 6.6 present the normal stress values in the x, y, and z directions at each loading step in laterite.

Table 6.5 Normal stress values in the x, y, and z directions on laterite tension face

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
1950	0.002	0.02	0
4875	0.006	0.10	0.002
9750	0.13	0.10	0.002
14625	0.019	0.15	0.003
19500	0.025	0.2	0.003

Table 6.6 Normal stress values in the x, y, and z directions on laterite compression face

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
1950	-0.001	-.0012	0
4875	-0.003	-0.029	0
9750	-0.006	-0.059	0.001
14625	-0.009	-0.088	0.002
19500	-0.012	-0.118	0.003

The Table 6.7 and 6.8 are obtained data for mud mortar joints, summarized in the table below, presents the normal stress values in the x, y, and z directions at each loading step in mud mortar.

Table 6.7 Normal stress values in the x, y, and z directions on mud mortar tension face

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
1950	0.001	.001	0
4875	0.002	0.02	0
9750	0.005	0.05	0
14625	0.008	0.07	0
19500	0.01	0.1	0.001

Table 6.8 Normal stress values in the x, y, and z directions on mud mortar compression face

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
1950	0	-0.004	0
4875	0.001	-0.010	0
9750	0.003	-0.019	0.001
14625	0.004	-0.029	0.001
19500	0.005	-0.038	0.001

Throughout the analysis, it was consistently observed that the highest peak stress occurred in the mud mortar used in the laterite block system. The failure predominantly transpired in the head joint of the mud mortar, precisely where the yield point was reached. It is noteworthy that this failure transpired under tension, indicating the susceptibility of the mud mortar to withstand tensile stresses. At the maximum applied load of 19,500 N, the mud mortar experienced a tension stress that reached its maximum allowable value. This critical stress level signifies the point at which the material can no longer sustain further loading, highlighting its limited tensile strength. These analysis outcomes provide valuable insights into the behaviour of the laterite block and mud mortar system under out-of-plane horizontal loading. The identification of the head joint in the mud mortar as a vulnerable location and the observation of tension failure underscore the importance of implementing appropriate reinforcement or design modifications to enhance the overall structural performance. To address the vulnerability of the mud mortar under tension, potential solutions may include incorporating reinforcement such as steel bars or fibers within the mortar, using alternative mortar materials with higher tensile strength, or employing additional design techniques such as providing additional lateral support to minimize the tensile stresses acting on the mud mortar. By considering these findings and implementing suitable measures, the structural performance and durability of the laterite block and mud mortar system can be significantly improved, ensuring its ability to withstand the applied loads and enhancing the overall safety and stability of the structure.

6.5.2 OUT OF PLANE ANALYSIS OF MASONRY WITH CEMENT MORTAR

In this case, a laterite prism with cement mortar was utilized to investigate the response of the masonry structure under different loading conditions. Figure 6.14 illustrates the imposition of Out-of-plane horizontal loading on prism with cement mortar.

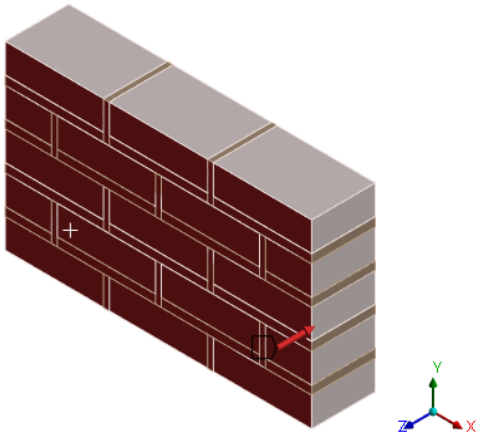


Fig 6.14 Imposition of Out-of-plane horizontal loading on prism with cement mortar.

For the analysis of Out-of-plane horizontal loading on a laterite masonry prism with cement mortar. The loading conditions represent incremental steps of applied loads, starting from 1550N, 11000N, 16500N, 22000N and 27500N. The purpose of these loading intervals is to simulate progressive loading on the masonry prism and observe its response to increasing external forces. By analysing the behaviour of the prism under different load magnitudes, we can gain understanding into its structural performance and potential failure mechanisms. By employing the normal stress method, the distribution of stresses within the prism was carefully evaluated. The normal stress values were recorded for each direction to understand the load-bearing capacity and potential failure modes of the structure. These values provide crucial information into the performance and structural integrity of the laterite masonry prism under Out-of-plane horizontal loading conditions. Figure 6.15 and 6.17 represents the tension face of the laterite block and cement mortar, showcasing areas where tensile stresses were prominent. Figure 6.16 and 6.18 depicts the compression face of the laterite block and cement mortar, illustrating regions where compressive stress are present.

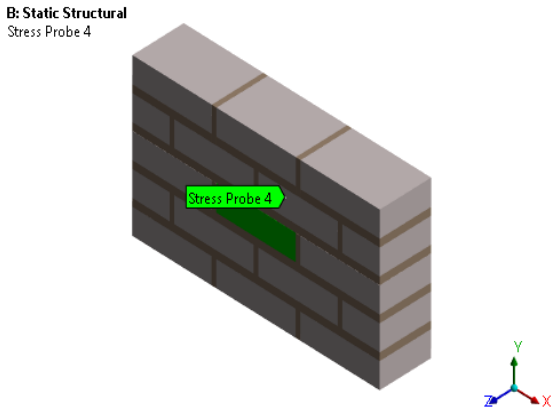


Fig 6.15 Tension face of laterite block

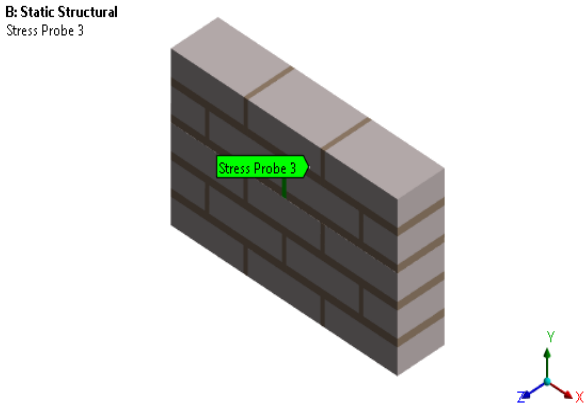


Fig 6.17 Tension face of cement mortar

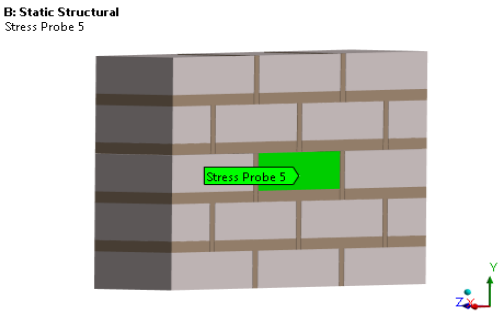


Fig 6.16 Compression face of laterite block

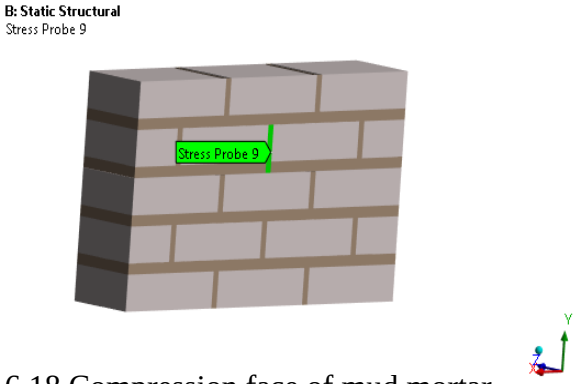


Fig 6.18 Compression face of mud mortar

Location of the areas of highest stress concentration within the laterite blocks and cement mortar joints, it helps to identify critical zones that require attention during the design and construction process. The Table 6.9 and 6.10 are obtained data for laterite blocks, summarized in the table below, presents the normal stress values in the x, y, and z directions at each loading step:

Table 6.9 Normal stress values in the x, y, and z directions on Laterite tension face

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
5500	0.007	0.06	0.001

11000	0.014	0.12	0.002
16500	0.022	0.18	0.003
22000	0.029	0.24	0.004
27500	0.036	0.3	0.005

Table 6.10 Normal stress values in the x, y, and z directions on Laterite compression face

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
5500	-0.003	-.0033	0.001
11000	-0.007	-0.067	0.002
16500	-0.01	-0.10	0.003
22000	-0.014	-0.13	0.004
27500	-0.017	-0.16	0.005

The Table 6.11 and 6.12 are obtained data for cement mortar joints, summarized in the table below, presents the normal stress values in the x, y, and z directions at each loading step:

Table 6.11 Normal stress values in the x, y, and z directions on Cement mortar tension face

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
5500	0.003	0.029	0
11000	0.007	0.057	0.001
16500	0.01	0.086	0.001

22000	0.014	0.115	0.001
27500	0.017	0.143	0.001

Table 6.12 Normal stress values in the x, y, and z directions 0n Cement mortar compression face

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
5500	0.001	-.0011	0
11000	0.003	-0.022	0
16500	0.006	-0.033	0
22000	0.009	-0.044	0.001
27500	0.012	-0.055	0.001

It was observed that the highest peak stress was experienced in the laterite blocks. Notably, the failure in the structure was first observed in the laterite blocks, specifically in tension. This indicates that the laterite material reached its yield point, or the point at which it could no longer withstand the applied stress, in tension. At a loading level of 27500 N, the stress in the laterite blocks reached its maximum tensile stress value. This indicates that the laterite material experienced its maximum tensile stress and was unable to sustain further loading beyond this point.

6.6 SUMMARY

The study focused on analyzing the behaviour of masonry structures constructed using laterite and different types of mortar, specifically mud mortar and cement mortar. The results of the study revealed the following findings:

1. Laterite and Mud Mortar:

   i. Failure occurred in the mud mortar at a lateral load of 19,500N stress.

   ii. The failure in the mud mortar was first observed in tension.

iii. The tension stress level in the mud mortar was significantly lower than the tensile stress level in the laterite when failure occurred.

iv. Failure of the mud mortar was observed when the laterite reached approximately 12.5% of its tensile stress level.

2. Laterite and Cement Mortar:

i. Failure occurred in the laterite at a lateral load of 27,500N stress.

ii. The failure in the laterite was first observed in tension.

iii. The tension stress level in the laterite was significantly lower than the tensile stress level in the cement mortar when failure occurred.

iv. Failure of the laterite was observed when the cement mortar reached approximately 11.89% of its tensile stress level.

6.7 IN-PLANE HORIZONTAL LOAD

The study on masonry structures plays a vital role in ensuring their structural integrity and safety. One such important loading scenario is In-plane horizontal loading, which occurs when external forces act parallel to the plane of the masonry wall or structure. In-plane horizontal loading can arise from various sources, including wind pressures, seismic forces, and lateral loads. These forces exert pressure on the masonry wall or structure, inducing bending moments, shear stresses, within the masonry units and mortar joints. The response of masonry structures to In-plane horizontal loading is influenced by several factors, including the mechanical properties of the masonry materials, the geometry and configuration of the structure, the presence of reinforcement, and the quality of construction. The mortar joints, which provide the connection between the individual masonry units, play a crucial role in transferring the in-plane forces between the units and distributing them evenly throughout the structure. Analysing the behaviour of masonry structures under In-plane horizontal loading requires computational methods, such as finite element analysis (FEA). These methods enable engineers to simulate the response of the structure, calculate the stresses and deformations, and assess the overall structural performance under different loading conditions. Understanding the effects of In-plane horizontal loading on masonry structures is crucial for designing structurally efficient buildings. It helps engineers make informed decisions regarding material selection, reinforcement strategies, and construction

techniques to enhance the structural capacity and resistance to in-plane forces. Figure 6.19 illustrates the application of In-plane horizontal loading.

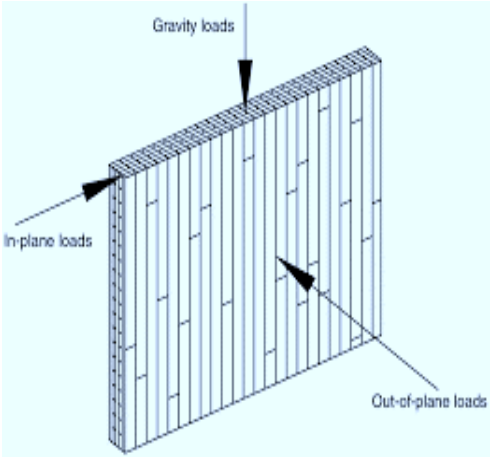
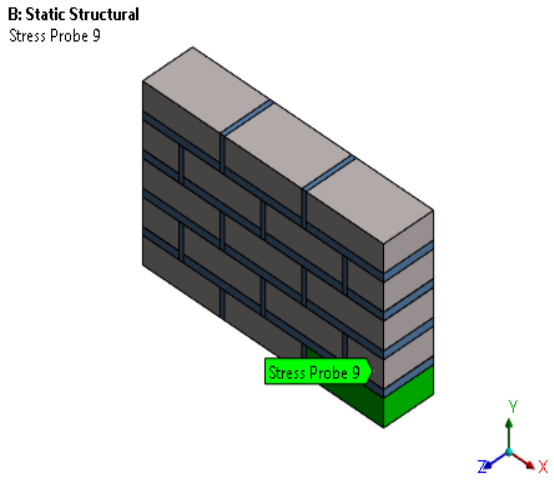


Fig 6.19 Application of In-plane horizontal loading.

6.7.1 IN-PLANE ANALYSIS OF MASONRY WITH MUD MORTAR

In the in-plane analysis of the prism constructed with laterite blocks and mud mortar, a comprehensive examination was conducted by subjecting the structure to varying loading conditions. For the analysis of In-plane horizontal loading on a laterite masonry prism with mud mortar. The loading conditions represent incremental steps of applied loads, starting from 2400N, 4800N, 7200N, 9600N and 12000N.The analysis aimed to assess the response of the masonry prism until it reached its yield point. To evaluate the strength development of the laterite blocks, the normal stress as criterion was employed during the analysis. This method allowed for a detailed assessment of how the laterite material performed under the influence of the applied loading while considering the yielding behaviour of the mud mortar in tension. By focusing on the normal stresses experienced in the X, Y, and Z directions, a comprehensive understanding of the load distribution and stress patterns within the masonry prism was achieved. These stress concentration zones play a crucial role in determining the structural behaviour and potential failure mechanisms of the masonry prism under In-plane horizontal loading conditions. Examining these areas provides valuable information into the behaviour of the joint materials under loading and assists in evaluating the overall stability and performance of the masonry prism. By analysing and visualizing the areas of highest stress concentration within the laterite blocks and mud mortar joints, it becomes possible to identify critical zones that require attention during the design and construction process. Understanding these stress distribution patterns aids in making informed decisions regarding

reinforcement strategies and material enhancements to enhance the overall strength and durability of the masonry structure. Figure 6.20 and figure 6.21 highlight the regions within the laterite block and mud mortar where the tensile stress values reached their peak.



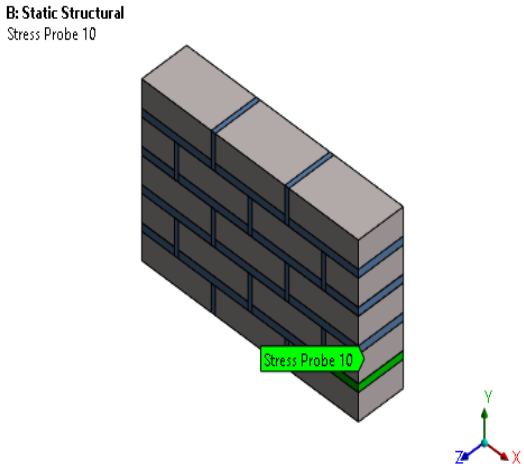


Fig 6.20 Tension face of laterite block

Fig 6.21 Tension face of mud mortar

The Table 6.13 and 6.14 are obtained data for laterite blocks and mud mortar, summarized in the table below, presents the normal stress values in the x, y, and z directions at each loading step in masonry prism with laterite bonded with mud mortar.

Table 6.13 Normal stress values in the x, y, and z directions in Laterite

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
2400	0.008	0.07	0.001
4800	0.01	0.1	0.002
7200	0.02	0.17	0.003
9600	0.03	0.2	0.004
12000	0.04	0.24	0.05

Table 6.14 Normal stress values in the x, y, and z directions in Mud mortar

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
2400	0.006	0.02	0
4800	0.01	0.04	0
7200	0.02	0.06	0.001
9600	0.027	0.08	0.001
12000	0.03	0.1	0.002

During the analysis, it was observed that the highest peak stress was observed in the mud mortar. This finding highlights the significance of the mortar in transmitting and distributing the applied loads within the masonry assembly. The stress concentration in the mud mortar indicates its crucial role in the overall structural performance. Furthermore, the failure in the mud mortar was specifically observed in the bed joint, where the yield point was reached. It is noteworthy that the failure occurred in tension. At the maximum applied load of 12000 N, the mud mortar reached its tensile stress value, indicating that it was subjected to its maximum capacity.

6.7.2 IN-PLANE ANALYSIS OF MASONRY WITH CEMENT MORTAR

In this case, a laterite prism with cement mortar was utilized to investigate the response of the masonry structure under different loading conditions. In the in-plane analysis of the prism constructed with laterite blocks and cement mortar, a comprehensive examination was conducted by subjecting the structure to varying loading conditions.

For the analysis of In-plane horizontal loading on a laterite masonry prism with cement mortar, the loading conditions represent incremental steps of applied loads, starting from 2500N, 5000N, 7500N, 10000N and 12000N**.**The applied loads includes a progressive

increase in magnitude. The analysis aimed to assess the response of the masonry prism until it reached its yield point. To evaluate the strength development of the laterite blocks, the normal stress method was employed during the analysis.. The figure 6.22 and figure 6.23 highlights the regions within the laterite block and cement mortar where the tensile stress values reached their peak.

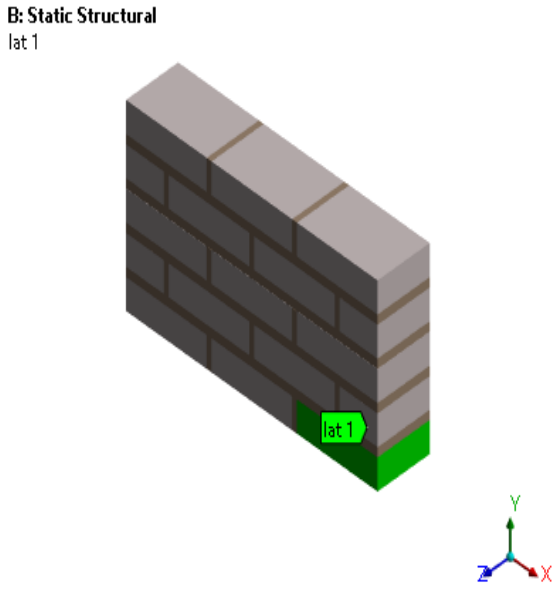


Fig 6.22 Tension face of laterite block

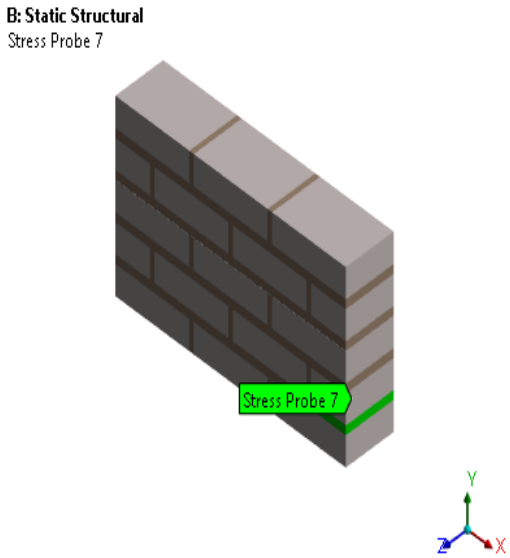


Fig 6.23 Tension face of cement mortar

This allowed for a detailed assessment of how the laterite and cement mortar performed under the influence of the applied loading while tension. By focusing on the normal stresses experienced in the X, Y, and Z directions, a comprehensive understanding of the load distribution and stress patterns within the masonry prism was achieved. These stress concentration zones play a crucial role in determining the structural behaviour and potential failure mechanisms of the masonry prism under In-plane horizontal loading conditions. By analyzing and visualizing the areas of highest stress concentration within the laterite blocks and cement mortar joints, it becomes possible to identify critical zones that require attention during the design and construction process. Understanding these stress distribution patterns aids in making informed decisions regarding reinforcement strategies and material enhancements to improve the overall strength and durability of the masonry structure.

Table 6.15 and 6.16 present the normal stress values in the x, y, and z directions at each loading step for laterite blocks and cement mortar.

Table 6.15 Normal stress values in the x, y, and z directions in Laterite

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
2500	0.009	0.07	0.01
5000	0.01	0.1	0.02
7500	0.02	0.2	0.03
10000	0.03	0.27	0.04
12500	0.04	0.3	0.06

Table 6.16 Normal stress values in the x, y, and z directions in Cement mortar

Load N	Normal Stress (x-direction) MPa	Normal Stress (y-direction) MPa	Normal Stress (z-direction) MPa
2500	-0.007	0.02	0
5000	-0.01	0.04	0
7500	-0.02	0.06	0
10000	-0.029	0.08	0.001
12500	-0.03	0.1	0.002

From the analysis, it was observed that the highest peak stress was observed in the laterite blocks, and failure occurred in the laterite material first, specifically in tension. As the applied load increased, the stresses within the structure intensified, and the laterite blocks experienced significant tensile stresses. Eventually, at an applied load of 12500 N, the laterite material reached its tensile stress value, indicating the point at which it could no longer

withstand the applied load and experienced failure. The failure occurred in tension within the laterite blocks, indicating that the material yielded and fractured due to the tensile stresses imposed on it. This observation highlights the importance of considering tensile strength in the design and analysis of masonry structures, particularly when laterite blocks are employed.

6.8 SUMMARY

The study focused on analyzing the behaviour of masonry structures constructed using laterite and different types of mortar, specifically mud mortar and cement mortar. The results of the study revealed the following findings:

1. Laterite and Mud Mortar:

i. Failure occurred in the mud mortar at a lateral load of 12,000N stress.

ii. The failure in the mud mortar was first observed in tension.

iii. The tension stress level in the mud mortar was significantly lower than the tensile stress level in the laterite when failure occurred.

iv. Failure of the mud mortar was observed when the laterite reached approximately 16.6% of its tensile stress level.

2. Laterite and Cement Mortar:

i. Failure occurred in the laterite and cement mortar at a lateral load of 27,500N stress.

ii. The failure in the laterite was first observed in tension.

iii. The tension stress level in the laterite was significantly lower than the tensile stress level in the cement mortar when failure occurred.

iv. Failure of the laterite was observed when the cement mortar reached approximately 2% of its tensile stress level.

CHAPTER 7
STRUCTURAL DEFECTS IN ANGADI PURAS

7.1 DEFECTS IN ANGADI PURAS

After conducting thorough field investigations, observations, surveys, and drawing upon life experiences, several common structural defects have been identified. These defects have developed over time due to various factors and can significantly impact the stability, durability, and overall structural integrity of buildings. The common structural defects seen in these historical buildings are:

i. Cracks in Masonry: Settlement-related structural defects often manifest as cracks in the masonry walls of historical buildings. As the building settles, the masonry units can experience stress, leading to the formation of cracks. These cracks appear horizontally, vertically, or diagonally, and their severity may vary depending on the extent of settlement. Cracks in masonry walls not only affect the aesthetics of the building but also weaken its overall structural integrity.

ii. Deterioration of Mortar Joints: The mud mortar joints used in the masonry of this historical buildings are susceptible to deterioration over time. Exposure to harsh weather conditions, including heavy rainfall and humidity, can cause erosion, weakening the mortar. Additionally, lack of maintenance and inadequate repair work contribute to the degradation of the mortar joints. This deterioration reduces the bond strength between the laterite blocks, leading to structural instability and potential collapse.

iii. Differential Settlement: One of the common structural defects seen in historical buildings is differential settlement. Differential settlement occurs when different parts of the building foundation settle at different rates, leading to uneven vertical movement. This can cause cracks to develop in the walls, floors, and ceilings of the building. In Kunnamkulam Angadi, the presence of varying soil conditions and inadequate foundation design can contribute to differential settlement issues.

iv. Displacement of Masonry Units: The inadequate bonding between the masonry units and the weak strength of the mud mortar can result in the displacement or bulging of

the laterite blocks. This displacement is often seen in the form of outward bulges or tilting of the walls. Factors such as inadequate construction techniques, lack of proper consolidation during construction, and uneven settlement of the foundation can contribute to this defect. The displacement of masonry units compromises the structural stability of the walls and increases the risk of structural failure.

v. Door and Window Misalignment: Settlement can also lead to the misalignment of doors and windows in historical buildings. As the foundation settles unevenly, it can cause the surrounding walls to shift, resulting in misaligned openings. This affect the functionality of doors and windows, making them difficult to open or close properly. Misaligned openings may also result in air and moisture leakage, compromising the building's energy efficiency and structural integrity.

vi. Fire Damage: Historical buildings with timber ceilings are susceptible to fire damage. In the event of a fire, timber can rapidly combust and weaken, compromising the structural integrity of the ceiling. Fire damage lead to the collapse of the ceiling, endangering the occupants and causing extensive damage to the building. Implementing fire prevention measures and considering fire-resistant materials and coatings can help mitigate the risk of fire-related structural defects.

vii. Foundation Cracks: Settlement-related structural defects can manifest in the form of cracks in the building's foundation. As the building foundation settles, it can experience stress and deformation, resulting in cracks. These cracks may appear vertically or diagonally in the foundation walls or at the junctions between the walls and the foundation. Foundation cracks not only compromise the structural integrity of the building but also allow moisture and pests to infiltrate, further exacerbating the problem.

viii. Inadequate Maintenance: Inadequate maintenance practices contributed to the deterioration of timber ceilings. Lack of regular inspections, repairs, and protective treatments accelerate the degradation of the timber members. Without proper maintenance, timber ceilings may experience structural defects such as warping, cracking, or splitting, making them more susceptible to further damage and compromising their overall structural stability.

ix. Insect Infestation: Insects, such as termites and wood-boring beetles, pose a significant threat to timber ceilings in this buildings. These pests can cause extensive damage by

tunneling through the timber, weakening its structure. The presence of insect infestation can lead to the deterioration of the timber members, including ceiling beams and joists. Regular inspections and appropriate treatment methods are necessary to prevent and control insect infestations in timber ceilings.

x. Lack of Reinforcement: Many historical buildings in Kunnamkulam Angadi were constructed without the use of reinforcement. This lack of reinforcement limits the load-carrying capacity and structural resilience of the buildings. As a result, the masonry walls may not have sufficient strength to withstand external forces, such as wind loads or seismic events. This increases the vulnerability of the structures and necessitates careful evaluation and retrofitting measures to enhance their structural stability.

xi. Lack of Structural Support: Timber ceilings in historical buildings suffer from a lack of adequate structural support. Over time, the original structural members, such as beams or trusses, weaken or deteriorate. This result in an insufficient load-bearing capacity to support the weight of the ceiling, leading to structural instability. The lack of proper structural support cause the timber ceiling to sag, crack, or even collapse if the issue is not addressed.

xii. Rot and Decay: Timber ceilings are susceptible to rot and decay, particularly in humid and moisture-prone environments. In Kunnamkulam Angadi, where the climate is characterized by high humidity, the timber members of the ceilings are at risk of moisture ingress. This result in the growth of fungi, leading to rot and decay of the wood. Rotting timber weakens the structural integrity of the ceiling, making it vulnerable to collapse or further deterioration.

xiii. Sagging or Bowing: One of the common structural defects seen in timber ceilings is the sagging or bowing of the ceiling elements. Over time, the timber members may lose their strength and stiffness due to factors such as moisture, insect infestation, or aging. This lead to the downward deformation or bowing of the ceiling, causing an uneven or sagging appearance. Sagging ceilings not only compromise the aesthetic appeal of the building but also indicate potential structural issues that need to be addressed.

xiv. Spalling of Laterite Blocks: Spalling refers to the gradual deterioration or loss of surface layers of the laterite blocks. In Kunnamkulam Angadi, spalling is commonly

observed due to exposure to moisture, weathering, and chemical reactions. The presence of spalling weakens the structural integrity of the blocks, making them more susceptible to further deterioration and damage. Spalled blocks may lose their load-carrying capacity and compromise the overall stability of the masonry walls.

xv. Tilting or Leaning Walls: Settlement-induced structural defects cause walls to tilt or lean. As the foundation settles unevenly, it exerts differential pressure on the walls, causing them to shift or tilt out of their vertical alignment. Tilting or leaning walls not only affect the appearance of the building but can also compromise its stability. In Kunnamkulam Angadi, where buildings may have been constructed on different types of soil, the risk of settlement-related defects is significant and visible in some structures.

xvi. Uneven Floors: Settlement can cause the floors of historical buildings to become uneven. As the foundation settles unevenly, it cause the floors to slope or tilt, leading to an irregular surface. This can be visually apparent and may result in issues with the alignment and stability of interior elements, such as furniture or fixtures. Uneven floors can also impact the functionality and aesthetic appeal of the building.

7.2 RETROFITTING METHODS FOR ANGADI PURAS

Retrofitting methods play a crucial role in preserving and strengthening historical buildings, particularly in Kunnamkulam Angadi. These traditional structures, with their unique architectural features, are valuable cultural heritage assets that require special attention for their conservation. Retrofitting becomes essential to enhance their structural integrity, ensure occupant safety, and prolong their lifespan. Here are some of the common structural retrofitting methods applied in these historical buildings:

i. Anchoring is a commonly employed retrofitting method in masonry structures, including historical buildings, to improve their structural stability and resistance to various forces. This technique involves the installation of anchors or ties that connect different components of the masonry assembly, such as walls, floors, or roofs, to enhance their overall structural integrity. Anchoring systems are designed to address issues such as inadequate lateral resistance, weak connections, or the separation of masonry elements. By creating a cohesive and

interconnected structure, anchoring helps distribute loads more efficiently and reduces the risk of structural failure. There are various types of anchors used in masonry retrofitting, including mechanical anchors, epoxy anchors, or grouted anchors. Figure .1 illustrates the diagram of Anchoring.

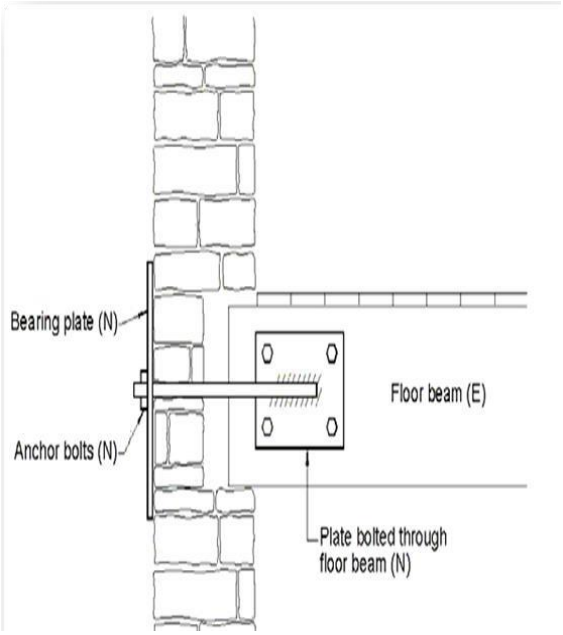


Fig 7.1 Anchoring

These anchors are selected based on the specific requirements of the structure and the load demands. They are strategically placed at predetermined locations, considering factors such as load paths, structural weaknesses, and the historical significance of the building. The anchoring process involves careful assessment and analysis of the existing structure, design considerations, and proper installation techniques. Special attention is given to the selection of anchor materials, compatibility with the masonry components, and load transfer mechanisms. The benefits of anchoring in historical buildings include improved resistance to lateral forces, enhanced structural stability, and preservation of architectural elements. Anchoring systems can also help prevent further deterioration and ensure the long-term sustainability of the structure. It is crucial to consult experienced professionals and follow appropriate guidelines and standards when implementing anchoring retrofitting in historical masonry buildings. Structural engineers and conservation specialists work together to design and execute anchoring solutions that balance structural integrity,

preservation principles, and aesthetic considerations.

ii. Base isolation is a prominent retrofitting method employed in masonry structures, including historical buildings, to mitigate the effects of seismic forces and enhance their seismic performance. This technique involves installing a flexible isolation system between the building's foundation and the ground, allowing the structure to move independently of the shaking ground during an earthquake. The base isolation system typically consists of isolation units or bearings made of materials with high damping properties, such as natural rubber, neoprene, or lead-rubber bearings. During an earthquake, the base isolation system allows the building to undergo controlled horizontal movements and vibrations, effectively dissipating the seismic energy and reducing the transmission of forces to the superstructure. This significantly decreases the likelihood of structural damage and enhances the overall seismic performance of the masonry structure. Base isolation offers several advantages as a retrofitting method. Firstly, it provides a high level of protection against seismic forces, minimizing structural damage and preserving the integrity of historical buildings. Secondly, base isolation effectively isolates the building from ground motions, resulting in reduced acceleration and displacement demands on the structure. This helps to safeguard not only the structural elements but also the valuable artifacts and contents within the building. Thirdly, base isolation can be designed to cater to specific site conditions and seismic hazards, ensuring a tailored retrofitting solution. It is important to note that the design and implementation of base isolation require careful consideration of factors such as building characteristics, site conditions, and seismic design criteria. Structural engineers and seismic experts perform detailed analyses and simulations to determine the appropriate type and configuration of isolation units, considering factors such as building weight, natural period, and seismic forces.

iii. Buttresses are structural elements designed to provide lateral support and reinforcement to existing walls, improving their stability and resistance against external forces. Buttresses are typically constructed adjacent to the existing walls, extending vertically from the foundation to the upper levels of the building. They consist of reinforced concrete or masonry elements that are connected to the

existing walls through proper anchoring techniques. The primary function of buttresses is to distribute and redirect lateral forces, such as wind or seismic loads, away from the vulnerable sections of the masonry walls. By transferring these forces to the foundation and the ground, buttresses enhance the overall structural stability and prevent excessive deflection or failure of the masonry walls. The design of buttresses takes into account various factors such as the type and condition of the existing walls, the magnitude of the lateral loads, and the architectural aesthetics of the building. Structural engineers perform detailed analyses to determine the optimal size, spacing, and reinforcement requirements for the buttresses, ensuring they effectively resist the applied forces. The addition of buttresses offers several advantages as a retrofitting method. Firstly, it provides immediate reinforcement to the existing masonry walls, reducing the risk of structural failure and improving overall stability. Secondly, buttresses can be designed to complement the architectural style of the building, preserving its historical aesthetics while enhancing its structural integrity. Thirdly, the construction of buttresses can be carried out with minimal disruption to the building occupants, as it is primarily an external retrofitting technique. Figure 7.2 illustrate various types of buttresses that could be constructed in historical buildings in Kunnamkulam.

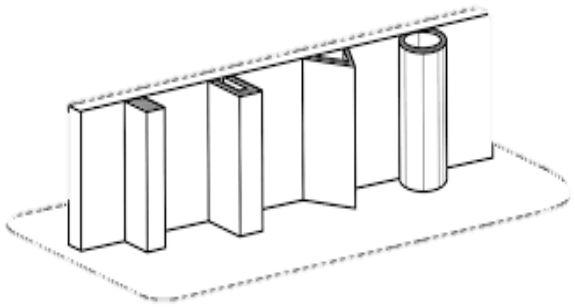


Fig 7.2 Various types of buttresses

iv. Carbon fiber reinforcement is a widely used retrofitting method in masonry structures, including historical buildings, to enhance their structural strength and performance. Carbon fiber sheets or strips, composed of high-strength carbon fibers embedded in a polymer matrix, are bonded to the surface of existing masonry elements. This technique is particularly effective in addressing issues

such as low tensile strength, cracking, and inadequate load-bearing capacity of masonry walls. Figure 7.3 illustrate carbon fiber reinforcement.

Fig 7.3 Application Carbon fiber reinforcement

v. External reinforcement with fiber-reinforced polymer (FRP) sheets is an effective retrofitting method that can potentially be employed in ancient laterite mud mortar structures in Kunnamkulam Angadi. Laterite mud mortar structures, commonly found in historical buildings, are known for their vulnerability to deterioration and structural weaknesses over time. To enhance their structural integrity and longevity, retrofitting techniques such as external reinforcement with FRP sheets can be utilized. FRP sheets are lightweight and high-strength composite materials that consist of fibers embedded in a polymer matrix. When applied externally to the surface of the laterite mud mortar structures, FRP sheets provide additional strength and stiffness to the weakened areas, effectively reinforcing the structure. This technique involves the application of FRP sheets to the external surface of masonry elements, such as walls or columns, to provide additional strength and improve their overall performance. FRP sheets are composed of high-strength fibers, such as carbon or glass fibers, embedded in a polymer matrix, typically epoxy resin. These materials offer excellent tensile strength, corrosion resistance, and lightweight properties, making them ideal for reinforcing masonry structures. The process of external reinforcement with FRP sheets begins with surface preparation, which involves cleaning, roughening, and

applying a bonding agent or primer to enhance adhesion. The FRP sheets are then cut to the desired size and shape and applied to the masonry surface using an epoxy adhesive or resin-based mortar. Once the FRP sheets are bonded to the masonry surface, they act as external reinforcement, effectively increasing the structures flexural and shear capacity. Figure 7.4 illustrate application of external reinforcement with fiber-reinforced polymer sheets to masonry walls.

Fig 7.4 Fiber-reinforced polymer sheets to masonry walls.

The sheets distribute loads and stress over a wider area, reducing localized damage and preventing the propagation of cracks. Additionally, the high tensile strength of FRP helps to resist external forces and improve the overall performance of the masonry element. External reinforcement with FRP sheets offers several advantages. Firstly, it provides a non-intrusive retrofitting solution that does not require extensive alterations to the existing masonry structure. This minimizes disruptions to the building occupants and preserves the architectural aesthetics of historical buildings. Secondly, FRP sheets are lightweight and easy to handle, making the installation process relatively quick and efficient. Lastly, FRP materials are durable, corrosion-resistant, and have a long service life, ensuring the long-term effectiveness of the retrofitting solution. It is important to note that the design and installation of external FRP reinforcement should be carried out by qualified professionals by relevant codes and guidelines.

vi. Grouting is another commonly employed retrofitting method in masonry

structures, including historical buildings. It involves the injection of a fluid material, known as grout, into the voids or cavities within the masonry walls to enhance their strength, stability, and durability. This is also a highly recommended method that can be implemented in Kunnamkulam Angadi .Grouting serves multiple purposes in the retrofitting process. Figure 7.5 illustrate application of grouting to masonry walls.

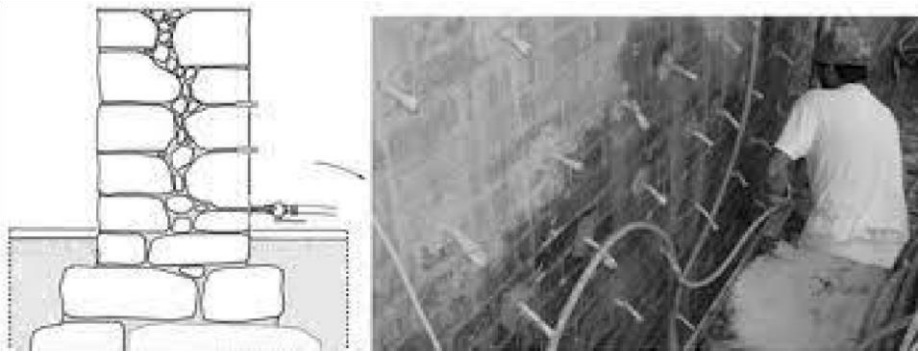


Fig 7.5 Application of grouting to masonry walls

Firstly, it helps fill the gaps and cracks present in the masonry walls, thereby improving their structural integrity and reducing the risk of further deterioration. The grout material, usually a cementitious mixture or epoxy-based compound, binds the loose or damaged components of the masonry, creating a cohesive and stable mass. Furthermore, grouting can provide additional support and reinforcement to the masonry walls. By injecting grout into the hollow cores or voids of the masonry units, it increases their load-carrying capacity and resistance to external forces, such as seismic or wind loads. This effectively strengthens the overall structure and improves its ability to withstand stress and deformations. Grouting can also contribute to the improvement of the thermal and acoustic properties of the masonry walls. The injected grout acts as an insulating layer, reducing heat transfer and enhancing energy efficiency. It can also dampen sound transmission, leading to improved acoustic performance within the building. The process of grouting involves drilling small holes or access points in the masonry walls at strategic locations. These holes are then used for injecting the grout material under controlled pressure. The selection of the grout material and injection technique depends on factors such as the condition of the masonry, the desired outcomes, and the specific requirements of the retrofitting project. It is

important to note that grouting should be performed by skilled professionals with expertise in masonry restoration and retrofitting. Proper evaluation of the existing masonry condition, selection of suitable grout materials, and precise injection techniques are essential to achieve the desired results and ensure the long-term effectiveness of the retrofitting process.

vii. Reinforcement with steel bars is a widely used retrofitting method employed in masonry structures, including historical buildings, to enhance their strength, durability, and resistance to various forces. This is also a highly recommended method that can be implemented in Kunnamkulam Angadi. This technique involves the insertion of steel bars, also known as reinforcement, into the masonry elements to provide additional tensile strength and improve overall structural performance. Steel bar reinforcement is typically installed in areas where masonry exhibits signs of weakness, such as cracks, spalling, or insufficient load-bearing capacity. The reinforcement bars are strategically placed in the mortar joints or embedded within the masonry units to create a composite structure that can withstand higher loads and stresses. The process of reinforcing masonry with steel bars begins with a thorough assessment of the existing structure to identify vulnerable areas and determine the appropriate reinforcement scheme. Structural engineers carefully analyse the load demands, material properties, and structural deficiencies to design an effective reinforcement strategy. The steel bars used for reinforcement are typically made of high-strength steel, such as carbon steel or stainless steel, to provide the necessary strength and corrosion resistance. The bars are inserted into pre-drilled holes or channels within the masonry elements and secured in place using epoxy grouts or cementitious mortars. Reinforcement with steel bars offers several advantages in masonry retrofitting. It increases the load-carrying capacity of the structure, improves resistance to bending and shear forces, and mitigates the effects of cracking and settlement. Additionally, steel bar reinforcement helps distribute loads more evenly throughout the structure, reducing localized stress concentrations and enhancing overall stability. It is important to note that the reinforcement design and installation should adhere to relevant codes, standards, and guidelines to ensure structural integrity and safety. Professional expertise and supervision are crucial during the retrofitting process

to ensure proper bar placement, adequate anchorage, and compatibility with the existing masonry components. Reinforcement with steel bars is a versatile retrofitting method that can be applied to various masonry elements, such as walls, columns, arches, and lintels. It provides a cost-effective and efficient solution to strengthen historical buildings, extending their service life and preserving their architectural heritage. Figure 7.6 illustrate application of reinforcement with steel bars on masonry walls.

Fig 7.6 Application of reinforcement with steel bars on masonry walls

viii. Shotcrete, also known as sprayed concrete or gunite, is a popular retrofitting method used in timber ceilings to provide additional structural strength and improve their overall stability. Figure 7.7 illustrate application of shotcrete.

Fig 7.7 Application of shotcrete

Shotcrete involves the application of a mixture of cement, sand, aggregate, and water under high pressure onto the surface of the timber ceiling. The process begins by preparing the surface of the timber ceiling, ensuring it is clean and free from debris. Reinforcement, such as steel mesh or rebars, may be added to enhance the structural integrity and prevent cracking. The shotcrete mixture is then pneumatically projected onto the ceiling surface using a spraying nozzle, propelled by compressed air. The high velocity of the spray compacts the concrete mix onto the timber surface, creating a durable and robust layer.

ix. Steel bracing is a commonly employed retrofitting method in masonry structures, including historical buildings, aimed at improving their structural stability and resistance to various loads. Minor versions of this retrofitting method have been observed in Kunnamkulam Angadi. Figure 7.8 illustrate application of Steel bracing.

Fig 7.8 Application of steel bracing

This technique involves the installation of steel elements within the masonry walls to provide additional support and enhance overall structural performance. Steel bracing addresses issues such as inadequate lateral resistance, vulnerability to seismic forces, and overall structural deficiencies. It offers several benefits, including increased structural strength, enhanced lateral stability, improved seismic performance, and minimal intrusion into the existing structure. In

historical buildings, steel bracing is applied to strengthen weak or deteriorated masonry walls.

x. Steel plates or straps are added to the timber ceiling elements, such as beams and joists, to enhance their load-carrying capacity. These steel elements are usually bolted or attached with epoxy to the timber members. The steel reinforcement provides additional strength and stiffness to the ceiling structure, improving its ability to withstand vertical loads and prevent excessive deflections. Minor versions of this retrofitting method have been observed in Kunnamkulam Angadi. Figure 7.9 illustrate application of Steel plates or straps.

Fig 7.9 Application of Steel plates or straps

xi. Timber splicing or sistering involves adding new timber sections adjacent to the existing ones. This technique is used when the existing timber members are weak or damaged. The new timber sections are either bonded to the existing ones using epoxy or connected with mechanical fasteners. By reinforcing the weakened areas, timber splicing or sistering restores the structural integrity of the ceiling and increases its load-bearing capacity. It is one of the most commonly observed methods in Kunnamkulam Angadi, particularly in the ancient churches, Figure 7.10 illustrate application of Timber splicing.

Fig 7.10 Application of Timber splicing

CHAPTER 8
CONCLUSIONS

Through comprehensive analysis of the laterite and mortar structures have aimed to verify and conclude the validity of the existing thumb rule stating that the strength of a masonry prism is considered as “failure based on highly reduced design strength” thumb rule, which is considered at times to the extending even upto 1/10th of brick strength, with specific reference to Table 8 in IS 1905(1987). Analysis, which included investigations into vertical loading, out-of-plane horizontal loading, and In-plane horizontal loading, has provided significant information’s that challenge the adoption of this thumb rule as a reliable standard in the construction industry.

- Findings indicate that the failure of the mud mortar occurred at significantly lower stress levels compared to the compressive strength and tensile strength of the laterite. Specifically, the vertical loading failure happened at approximately 2.09% of the laterite's compressive stress level, while the Out-of-plane horizontal and In-plane horizontal loading failures occurred at 12.5% and 16.6% of the laterite's tensile stress level, respectively. These results highlight the critical role of mortar strength and behaviour in the overall structural integrity of masonry constructions Thus, we can confidently conclude that the commonly employed "1/10th of the brick strength at joint failure” is not a reliable guideline for masonry construction. It is evident that more importance should be given to the quality and strength of the mortar used rather than solely focusing on the masonry blocks alone. Furthermore, analysis revealed that the laterite, when combined with cement mortar, experienced failure when the cement mortar reached approximately 0.26% of its compressive stress level in vertical loading, 11.89% of its tensile stress level in Out-of-plane horizontal loading, and 2% of its tensile stress level in In-plane horizontal loading. This comparison highlights the superior performance of cement mortar over mud mortar and reinforces the importance of using high-quality mortar in masonry construction projects.
- It is crucial to note that the compressive strength of the laterite samples collected from Kunnamkulam Angadi was determined to be 3 MPa, as per the Indian Standard IS 3620:1989, the minimum compressive strength requirement for laterite blocks was

specified as 2.5 MPa. Additionally, the observed variation in the thickness of mortar joints among different houses during our fieldwork indicates a lack of uniformity in construction practices and raises concerns about the overall structural integrity of the buildings.

- The analysis revealed that failure occurred in the mud mortar under a vertical stress of 0.5 MPa in the laterite mud mortar prism for vertical loading. In addition, failure was observed in the mud mortar at an Out-of-plane horizontal load of 19,500N stress and an in-plane horizontal load of 12,000N stress in the laterite mud mortar prism. These findings emphasize the importance of considering the quality and strength of the mortar, as it significantly influences the performance and failure mechanisms of the masonry structure, especially in a seismic zone.
- Considering the seismic zone of Kunnamkulam, it is evident that the structural defects observed in the old Angadi Puras, such as tilting or leaning walls, spalling of laterite blocks, sagging or bowing in timber ceilings, rot and decay in timber ceilings, displacement of masonry units, and cracks in masonry, pose significant risks during seismic events. Therefore, the importance of retrofitting methods to enhance the resilience and safety of these structures cannot be overstated.

The study challenges the validity of the "1/10th Strength" thumb rule as a reliable standard for estimating the strength of masonry prisms at joint failure. This study highlights the limitations of the existing thumb rule and emphasizes the importance of using high-quality mortar in masonry construction. It provides valuable information's for professionals in the construction industry to make informed decisions and implement improved standards based on the strength and behaviour of the mortar in conjunction with the masonry block. The analysis of the laterite and mud mortar structures in Kunnamkulam Angadi highlights the critical role of high-quality mortar in masonry construction. Furthermore, it emphasizes the critical need for comprehensive and focused structural studies within the seismic Zone III of Kunnamkulam to enhance the structural stability of these homes. By employing precise retrofitting methods, one can effectively safeguard these structures without compromising their cultural heritage. These studies should prioritize structural integrity over architectural beautification, as the safety of the occupants during seismic events is of paramount importance. It is imperative to recognize that Kunnamkulam falls within a seismic zone III

which is considered a moderate seismic hazard zone, highlighting the urgency and relevance of such studies in this specific geographical context. Implementing retrofitting measures and conducting further research in this regard will be essential to ensure the resilience and safety of the existing structures in Kunnamkulam Angadi.

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